# MAINTENANCE OPTIMIZATION PROGRAMME FOR NUCLEAR POWER PLANTS

# CASE STUDIES




INTERNATIONAL ATOMIC ENERGY AGENCY

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ANNEX I.
# MAINTENANCE CONCEPT IN LOVIISA NUCLEAR POWER PLANT

***Fortum Case Study***

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**Summary**

The maintenance concept of Loviisa power plant is the result of long and determined development work. The maintenance model is under constant development, based on the experience gained both within Loviisa and from other power plants. With the help of the concept, the maintenance unit of Loviisa power plant has been able to fulfil the constantly tightening demands on the safe and reliable operation of a nuclear power plant and to be competitive and efficient with regard to costs.
Development work on the maintenance concept in Loviisa was started in 2002. At this time the need and potential for developing O&M functions was recognized. Such development has helped to guide the maintenance processes as an important part of the power plant's decision–making. The former maintenance programme did not fulfil today's demands on maintaining the power plant's operability. It was largely founded upon periodic actions instead of the actual condition of equipment. The basis of actions and periodization were no longer clear nor were they consistent or common for similar equipment. Maintenance tasks were not prioritized according to the safety and production aspects of equipment. As a result resources could not be focused to the actions and objects which guarantee reliable and safe electricity production.

## I-1. MAIN REASONS AND TARGET SETTING FOR MAINTENANCE CONCEPT DEVELOPMENT

Fortum's aim was to increase the productivity of capital due to intensifying competition. The main goal was set as maintaining and increasing the usability of the equipment to ensure safe and reliable production in the ageing plant. In order to achieve the target plant reliability the efficiency of the organization should be kept as high as possible. Fulfilling targets with properly prioritized investments, plant efficiency, and productivity will be ensured over the lifetime of the plant.

At the same time a new plant information system was under construction and it created a great opportunity to change O&M practices and processes. New maintenance strategies and processes were configured into the system in order to allow it to enable better maintenance management through KPI monitoring.

Previously the plant was monitoring only visible costs (FIG. I-1) and actual cost causes were not clearly known. The O&M aim should be to identify the hidden costs and causes in order to be able to achieve high availability and safety.

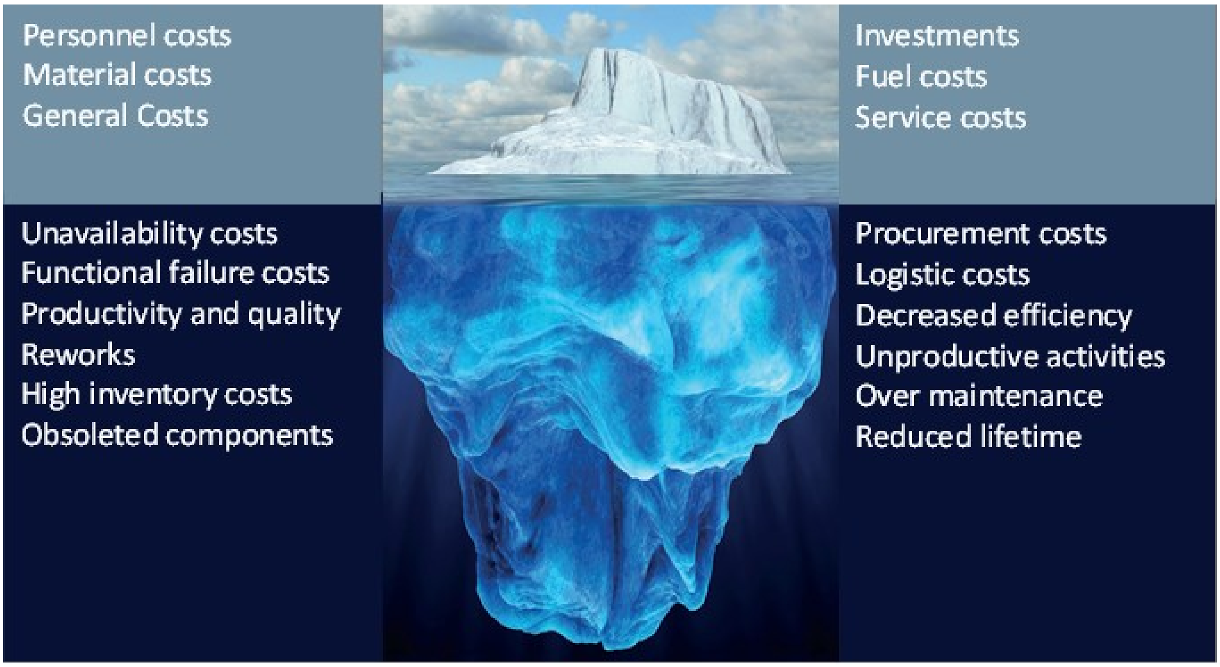



*FIG. I-1. Iceberg of visible and hidden costs and causes.*

## I-2. STEPS OF MAINTENANCE CONCEPT DEVELOPMENT

### I-2.1. Evaluation of plant CMMS and data

During the evaluation process it was identified that the old CMMS does not contain all of the required data for maintenance development. A list of additional necessary data includes:

- Labour hours;
- Labour costs;
- Material costs;
- Equipment criticality classification;
- Equipment strategies;
- Functional and non–functional failure separation;
- Reworks;
- Observation and failure hierarchies.

All required functionalities were developed into the new plant information system. This enabled and ensured better maintenance KPI monitoring, analysing and corrective action planning and execution.

### I-2.2. Definition of maintenance strategies

Five new maintenance strategies were developed (FIG. I-2), as well as four operative strategies (four–tier approach) for the components, and one strategy to connect all of these procedures.

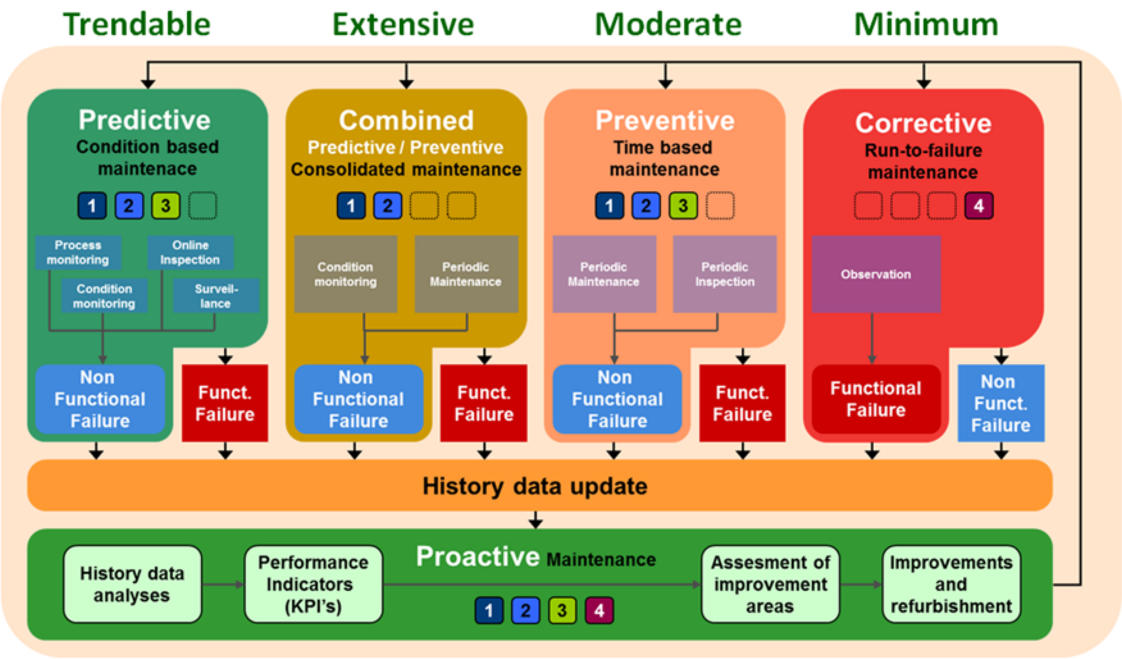



*FIG. I-2. Enhanced tiered maintenance strategy (like INPO AP–913).*

### *I-2.2.1. Predictive*

Predictive maintenance is based on the equipment condition and performance; during the maintenance tasks equipment remains available, and based on the collected information corrective actions will be defined. Condition monitoring can be on–line or off–line depending on equipment type and criticality.

Condition based maintenance tasks are for example:

- Process parameter monitoring;
- Vibration monitoring;
- On–line inspections;
- Surveillance;
- Thermography;
- Acoustic emission;
- Oil analysis.

### *I-2.2.2. Preventive*

Preventive maintenance is time based and is used for the components where condition based maintenance is not justified. During the maintenance equipment are unavailable.

Time based maintenance tasks are for example:

- Periodic overhaul;
- Periodic inspections;
- Oil change.

#### *I-2.2.3. Combined*

Combined equipment strategy covers the most critical plant equipment in criticality classes 1 and 2. Part of the criticality class 3 equipment may also be included within the scope of this strategy. Combined strategy consists of preventive and predictive maintenance tasks.

#### *I-2.2.4. Corrective (Run–To–Failure)*

Equipment in this strategy does not have any pre–planned predictive or preventive maintenance tasks. Only visual observation rounds are used to track equipment condition. Functional failures are allowed in this strategy.

#### *I-2.2.5. Proactive*

Proactive maintenance utilizes the results of tasks of operative maintenance strategies and identifies improvement areas. Corrective actions will reduce the costs and increase equipment reliability, and maintainability, as well as the organization's performance.

## I-3. FUNCTIONAL AND NON–FUNCTIONAL FAILURES

Functional and non–functional failures are focused against equipment under the selected operative strategy. Equipment functional failures in predictive, preventive or combined strategy should be analysed and corrective actions defined. Causes of the functional failures might be:

- Maintenance tasks are not properly set;
- Human error during the maintenance;
- Operation errors;
- Obsolescence of components;
- Environmental conditions.

### I-3.1. Functional failure

Termination of the ability of an item to perform a required function [28].

### I-3.2. Non–functional failure

Equipment condition is decreased but not failed. Equipment is still able to perform required function but performance is decreased.

### I-3.3. Maintenance KPI

The performance of the organization is compared against strategic goals. KPI (FIG. I-3) show a logical, step–by–step connection between strategic objectives in the form of a cause–and–effect chain. Performance is monitored from four perspectives:

- Financial;
- Customer and interest groups (e.g. local authorities);
- Processes and effectiveness;
- Learning and growth;
- Good results and efforts in learning and growth enable better results from three other perspectives.

| | Maintenance KPI March 2012 | | | | |
|---|---|---|---|---|---|
| | Laji | Actual | Target | Status | Direction |
| Financial | Maintenance Costs | ######## | ######## | | |
| Customer and Interest Groups | Amout of LCO Workorders | ######## | ######## | | |
| | Backlog of Corrective Actions | ######## | ######## | | |
| Processes and Effetiveness | Maintenance Costs/Production €/MWh | ######## | ######## | | |
| | Amount of Workorders | ######## | ######## | | |
| | On-Time Delivery (%) | ######## | ######## | | |
| | Service Level (%) | ######## | ######## | | |
| Learning and Growth | Training Hours per person | ######## | ######## | | |
| | Development Discussions (%) | ######## | ######## | | |
| | Sick Leaves (%) | ######## | ######## | | |

*FIG. I-3. Maintenance Key Performance Indicators chart.*

KPI matrix compares actual values for the set up target and status is shown in coloured emoticon figures with coloured arrows which show direction (FIG. I-4). Lower level indicators drills down from unit level to group level, e.g. mechanical maintenance.

| KPI | Actual | Target | Status | Direction |
|---|---|---|---|---|
| Mechanical maintenance On time delivery % | 89,6 % | > 88 % | | |

*FIG. I-4. Lower level indicator on–time delivery in mechanical maintenance.*

## I-4. CRITICALITY CLASSIFICATION

The objective is to identify critical components for the plant production and safety. Optimal maintenance strategy for the equipment is based on the classification. Classification is used in planning of maintenance programmes and spare part strategy. All components are classified in one of the four classes 1 to 4 (FIG. I-5). Classification is grounded on the production, safety, availability and authority requirements for the equipment taking into account maintenance and replacement costs.

Criticality class for each equipment is based on following criteria:

- Production loss because of the equipment failure:
  - Failure = most probable functional failure of the equipment;
- Safety related equipment (Technical Specification, LCO and Fussell–Vesely (FV) risk):
  - Safety risk in the flow chart is taken account by using FV risk importance value based on PSA analysis;
- Requirement for equipment in directives or regulations;
- Maintenance is economically justified.

Classification can be changed based on operation and maintenance experience or change in risk analysis.

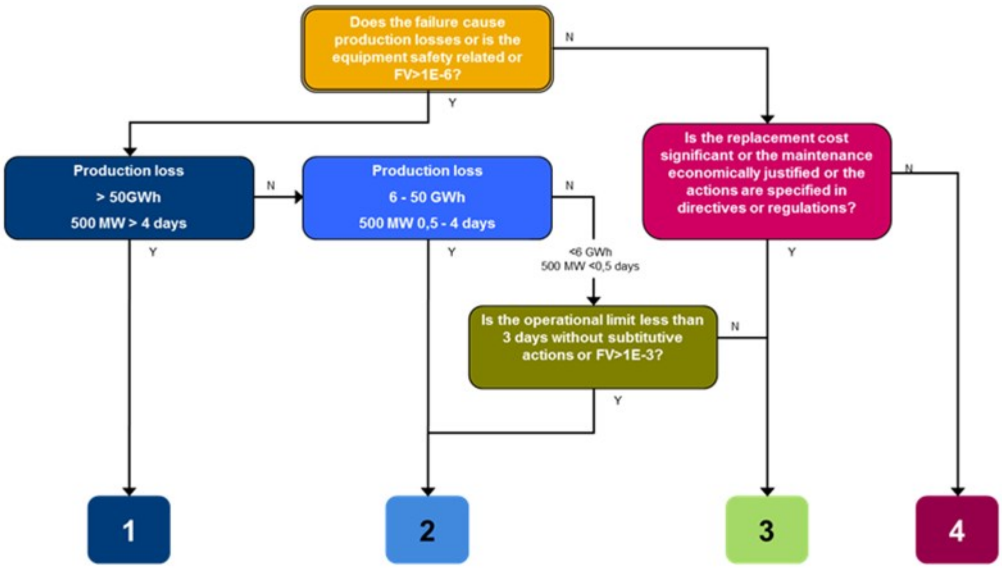



*FIG. I-5. Criticality classification flow chart.*

Proportions of equipment for different criticality classes are shown in FIG. I-6.

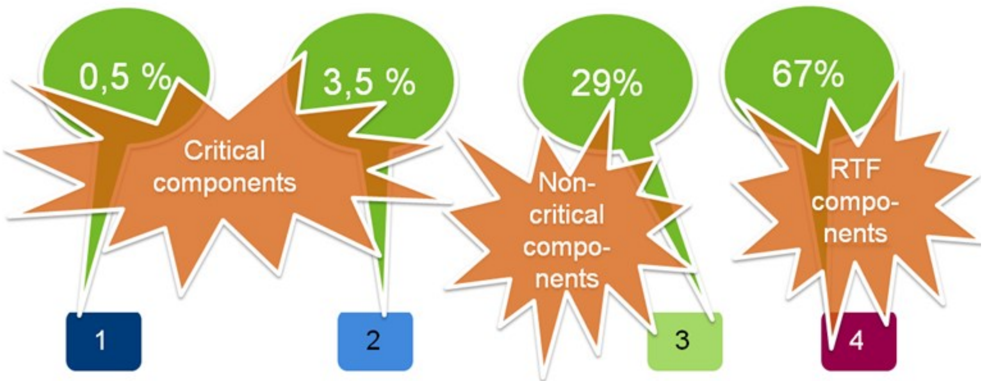



*FIG. I-6. Equipment proportion in different criticality classes.*

## I-5. SELECTION OF MAINTENANCE TASKS

Maintenance tasks selection is based on equipment and function criticalities (FIG. I-7). Equipment functions in criticality classes 1 to 3 need to be identified and analysed. For the critical functions there should be predictive or preventive maintenance tasks to prevent functional failure. In the case that failure mechanism cannot be identified the risk for the failure should be accepted or failure should be eliminated by modernization. In addition to the equipment main function there can be sub–functions which are not critical and maintenance tasks for those functions are not needed.

Criticality class 4 equipment belongs automatically to RTF strategy in cases where no pre–planned maintenance tasks exist.

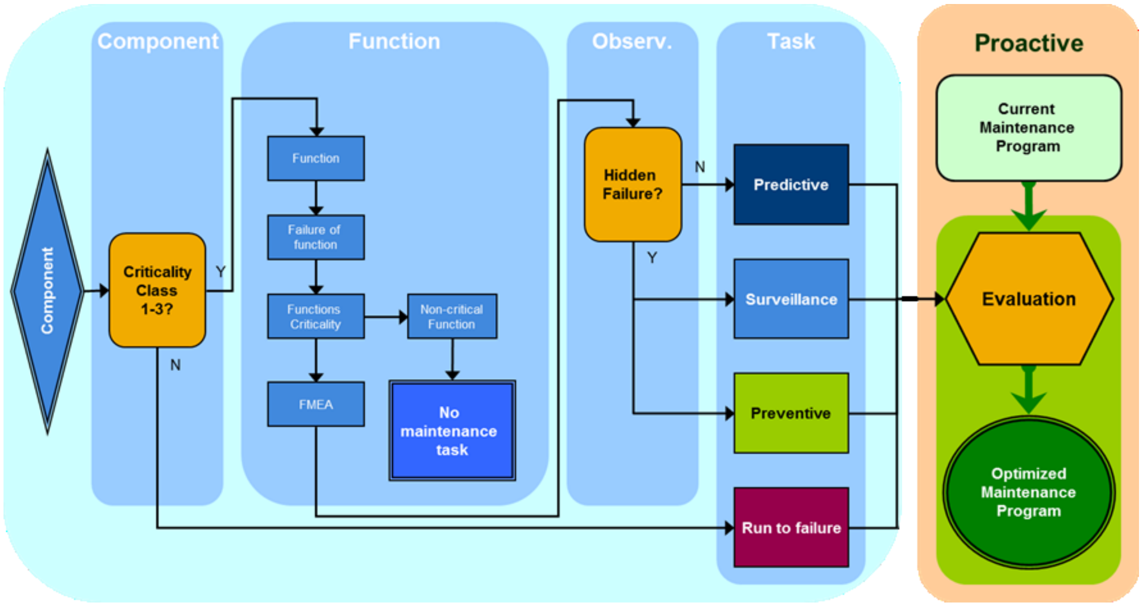



*FIG. I-7. Selection of maintenance tasks.*

### I-5.1. Evaluation of current maintenance programme and selection of targets for improvement

Analysis for the current maintenance programme was conducted for the selected equipment groups (motors, pumps, valves etc.). Selection was focused on areas with great need for potential optimization and where the advantages of such optimization were also great. Maintenance templates were used to identify improvement areas. In templates maintenance tasks for the selected equipment groups were divided based on the following criteria:

- Equipment type (centrifugal pump, grease lubricated motor, etc.);
- Criticality class (1–3);
- Operating hours per year;
- Operating condition;
- Maintenance template shows maintenance programmes current state (tasks, frequencies etc.).

### I-5.2. Optimization of maintenance programmes for selected areas

The following maintenance areas were identified via the process as being potential targets for improvement:

Case 1: Strategy change from predictive and preventive to RTF strategy;
Case 2: Evaluation of current maintenance tasks for grease lubricated centrifugal pumps;
Case 3: Optimized maintenance tasks for actuators of motor operated valves;
Case 4: Optimization of reactor containment isolation valves leak test;
Case 5: Optimization of maintenance programme for electrical motors;
Case 6: Optimization of the rotating equipment vibration measurement frequencies;
Case 7: RCM analysis for main seawater pumps and motors;
Case 8: RCM analysis for primary circulation pumps;
Case 9: Containment leakage test interval change from 4 to 8 years;
Case 10: Optimization of I&C maintenance tasks.

More information about the cases is given in Attachment.

### I-5.3. Determination of optimization methods

Determination of optimization methods depends on equipment criticality and costs. For the critical components in classes 1 and 2 the most advanced tools for optimization are used, such as full scope RCM analysis (see Attachment cases 7, 8 and 9).

Maintenance tasks for non–critical components are optimized by using maintenance task flowcharts (see Attachment cases 2, 3, 5, 6 and 10).

### I-5.4. Enhancements of CMMS to support new maintenance concept

The previous CMMS did not fully support the new maintenance operating model. The old information system did not enable adequate data collection and the quality of data did not fulfil the new requirements. A new plant information system was developed to support the new maintenance concept.

The new plant information system contains the following new functionalities:

- Three level observation hierarchy;
- Functional and non–functional failure classification;
- Failure mechanism and cause classification;
- Costs (resources, materials and services);
- Clearance management;
- Work impact classifications;
- Mobile devices.

### I-5.5. Comparison of current and new maintenance programmes

The optimized new maintenance programme and the current maintenance programme are compared when changes in the maintenance programme have been implemented. The comparison is performed by analysing the maintenance KPIs such as equipment availability, functional failures and maintenance costs. If these analyses reveal deviations, their causes and corrective actions should be defined. Maintenance optimization is a continuous process and maintenance programmes can be changed based on this running analysis.

### I-5.6. Implementation of new maintenance programme

New and optimized maintenance programmes are implemented continuously. Before new and optimized programmes are put into use all relevant maintenance instructions will be updated and approved before being added to the CMMS. If necessary, training will be organized.

Definition of the process for maintenance feedback (4Ws = Who, What, Where and When).

The maintenance feedback process is an important and crucial part of proactive maintenance and maintenance management. Feedback information is fed directly to the system by the person who has first–hand information, for example failure history is updated by the workers.

Feedback data is inspected and approved by maintenance line managers for example supervisors make inspections and group managers give the approval or requirements for feedback correction. FIG. I-8 describes Loviisa NPP's feedback process.

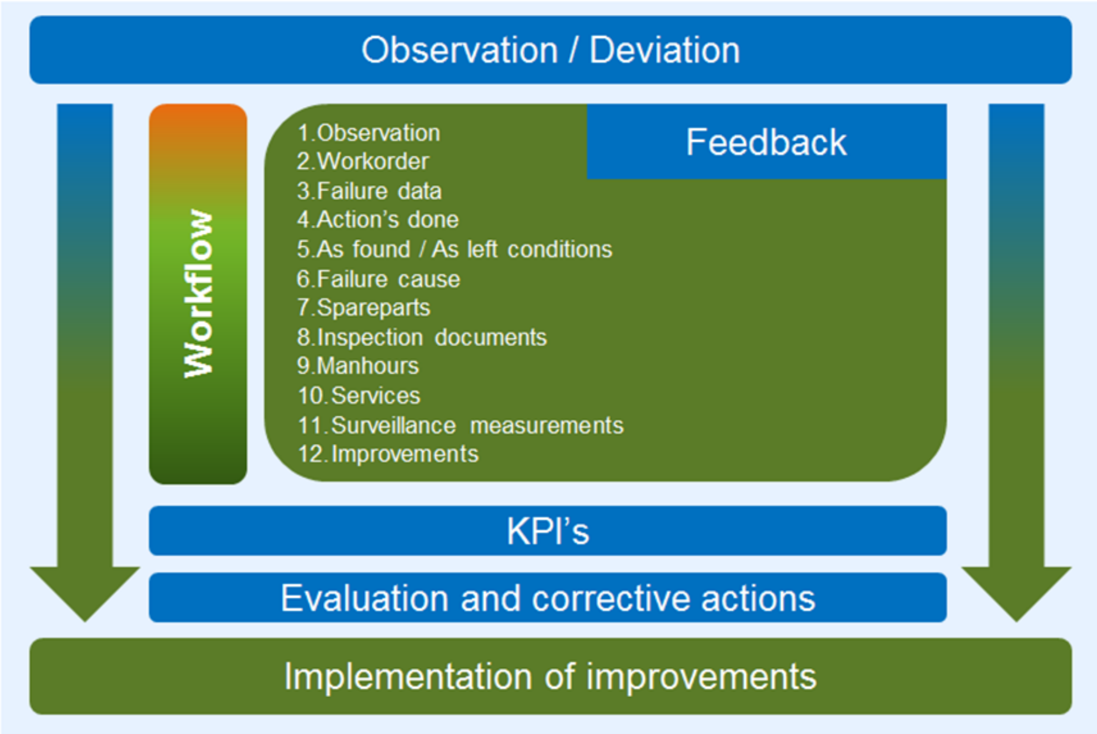



*FIG. I-8. Operations and Management feedback process.*

### I-5.7. Monitoring of maintenance KPI

In maintenance unit there are 11 KPI and approximately 130 lower–level indicators. KPI monitoring is done by the maintenance managers and supervisors on a daily basis. All KPI are reviewed at a monthly maintenance managers meeting and all deviations will be analysed and decisions for corrective actions is made (CAP process).

### I-5.8. Dynamic trending of maintenance backlog

Maintenance backlog (amount of open Work Orders and man hours) is one of the most important KPI (FIG. I-9). Dynamic trending feature enables managers to follow workloads from unit level to single supervisor level by using drill–down functionality.

Backlog can be filtered using different criteria, such as:

- Asset criticality class;
- Work priority;
- Technical specification/LCO;
- Workgroup;
- Supervisor group;
- Maintenance group;
- Work type;
- Time period (year, month, day).

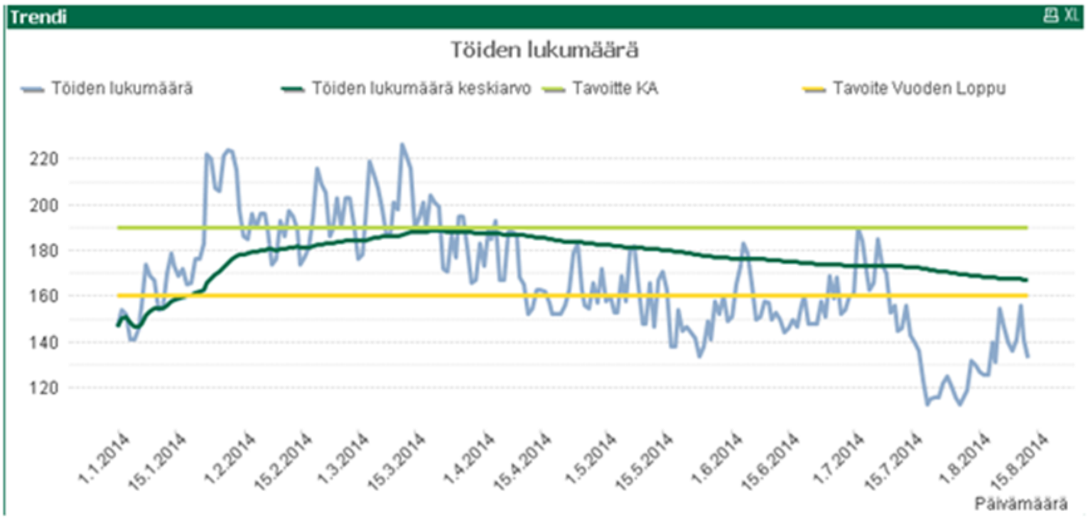



*FIG. I-9. Maintenance dynamic backlog.*

Blue trend line shows current status of backlog and green trend line shows average value. Light green line indicates target average value and yellow line indicates target value in the end of year.

## I-6. ANALYSIS OF DEVIATIONS AND CORRECTIVE ACTIONS PROCESS

The maintenance concept is steered by company drivers like high availability requirements and authority requirements and is developed to fulfil those requirements. It is a continuous optimization process which requires strong commitment from plant managers.

Maintenance concept is divided into three sections (FIG. I-10):

- Maintenance programme and evaluation;
- Problem screening process;
- Optimization process.

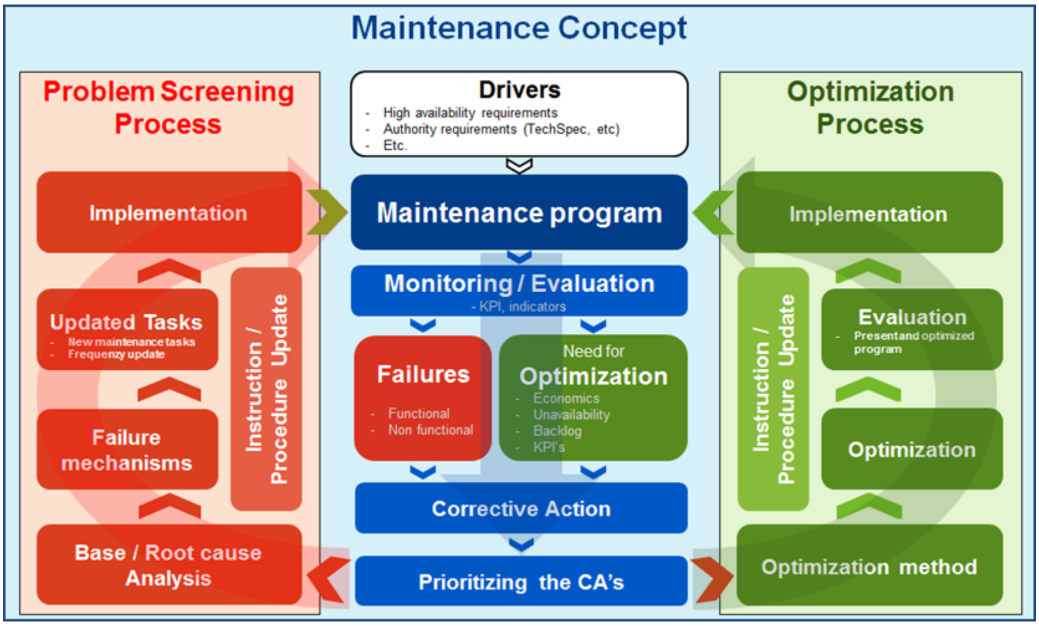



*FIG. I-10. Maintenance programme lifecycle.*

## I-7. PLANT LIFETIME MANAGEMENT

Maintenance concept is a major part of the Plant Lifetime Management (PLIM) Programme. PLIM process utilizes plant information and data from different functions. In Loviisa the technology unit is responsible for the organization of the PLIM programme.

Its main functions are (FIG. I-11):

- System responsibilities (system engineers);
- SSC analysis;
- Ageing and failure mechanism analysis;
- Forecasting of remaining age of the SSC;
- Quality control;
- System health reporting;
- Coordination of investments and improvements.

The PLIM goal is to ensure high performance of SSC for the remaining operation license period.

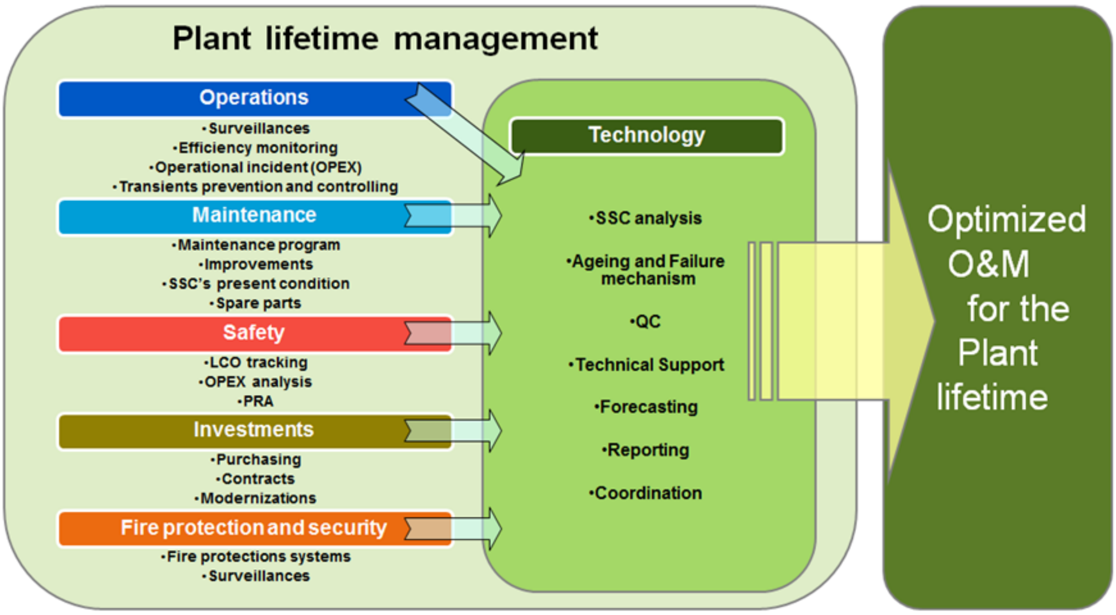



*FIG. I-11. Plant Life Management Programme.*

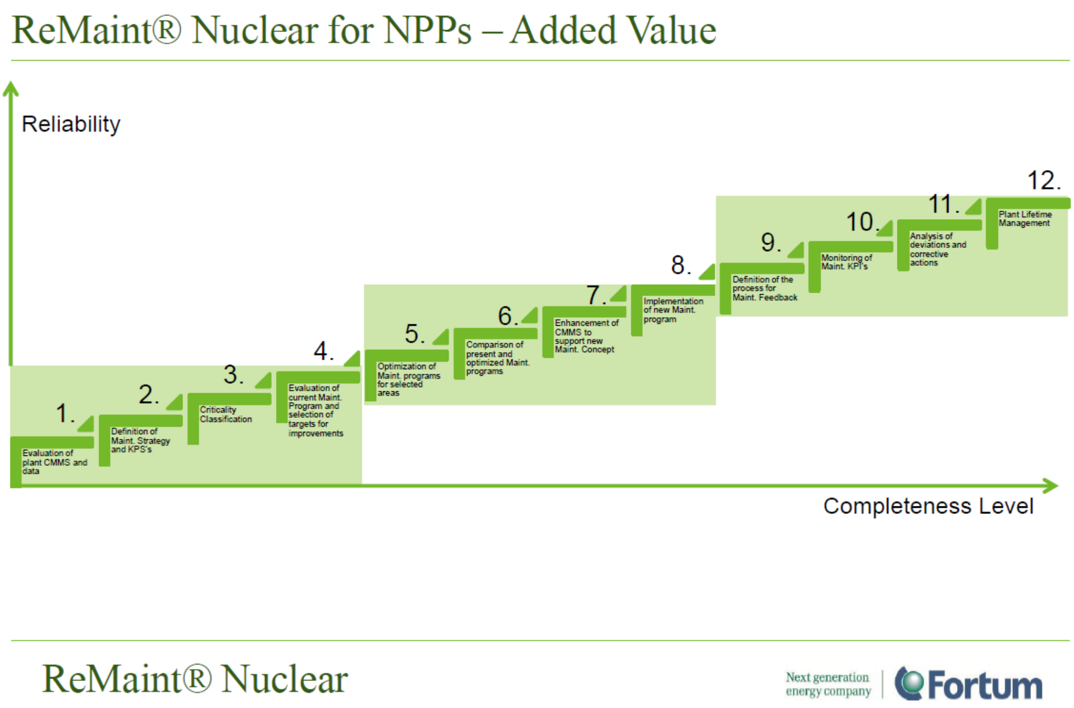
## I-8. CONCLUSION

Fortum Power and Heat operates world's most efficient VVER–440 nuclear power plant in Loviisa. Long–time average capacity factors for both reactors are more than 90%. One of the key elements to achieve high capacity factors is the sophisticated maintenance concept which ensures safe, reliable and profitable production.

**ATTACHMENT TO ANNEX I**
**FORTUM LOVIISA CASE STUDY**

This attachment contains a series of slides with additional information to the Fortum case study.

ReMaint® Nuclear Concept is a management model of nuclear power plant maintenance and it consists of twelve steps including maintenance strategies, criticality classification, maintenance optimization and feedback loop with KPIs. Slide below shows concepts twelve different steps.




Current maintenance program status was analysed by using equipment category grouping and maintenance templates. Based on the status analysis prioritization for improvements areas were made. The slide below describes how the grouping was made.

## Evaluation of current maintenance program and selection of targets for improvement

- Analyze of current maintenance program was made for the selected equipment groups (motors, pumps, valves etc.)
- Maintenance tasks for the selected equipment groups were divided based on the following criteria's
  - Equipment type (centrifugal pump, grease lubricated AC motor, etc.)
  - Criticality class (1-4)
  - Operating hours per year
  - Operating condition
- Information was shown on maintenance templates
- Template shows maintenance programs current state (tasks, frequencies etc.)
- Selection has been focused to areas with the best cost-benefit ratio (costs, availability, risks)
- Maintenance program optimization is done by using different optimization methods

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Ten different cases how to optimize maintenance in practice by using different optimization methods was used.

## Development and optimization of Maintenance Concept - **In practice**

- **Case 1:** Strategy change from predictive and preventive to RTF strategy
- **Case 2:** Evaluation of Current Maintenance Tasks for Grease Lubricated Centrifugal Pumps
- **Case 3:** Optimized Maintenance Tasks for Actuators of Motor Operated Valves
- **Case 4:** Optimization of Reactor Containment Isolation Valves Leak Test
- **Case 5:** Optimization of maintenance program for electrical motors
- **Case 6:** Optimization of the rotating equipment's vibration measurement frequencies
- **Case 7:** RCM analysis for Main seawater pumps and motors
- **Case 8:** RCM analysis for Primary Circulation Pumps (PCP)
- **Case 9:** Containment leakage test interval change from 4 to 8 years
- **Case 10**: Optimization of I&C maintenance tasks

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Case 1 shows direct savings when Run–to–Failure strategy is taken in use for criticality class 4 equipment's.

## Case 1: Strategy change from predictive and preventive to RTF strategy (Equipment criticality class → 4)

4

Driving force to utilize maintenance resources more efficiently and to reduce maintenance costs in Loviisa Nuclear Power Plant.

- Criticality classification project was performed 2004-2005 in Loviisa NPP
- Less critical components consist of 67% of plant assets
- Maintenance programs of less critical components were updated to Run To Failure (RTF) strategy
- Quick results were achieved:
  - 2500 predictive and preventive maintenance tasks terminated
  - Release of resources for more important tasks (safety and performance)
  - Reduction of 6 FTE
  - **0,5 M€/year savings**

2500 maintenance tasks terminated

Release of resources, 10000 man-hours in total

=

6 FTE resources free for more productive work

1 2 3

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Case 2 shows how maintenance templates are used to collect present maintenance tasks for selected equipment groups to identify targets of improvements.

## Case 2: Evaluation of Current Maintenance Tasks for Grease Lubricated Centrifugal Pumps

2 3

**Centrifugal Pump, Grease lubricated**

| | Equipment class | 2 | | | | | | | | 3 | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Duty cycle | Long | | Moderate | | Short | | Outage | | Long | | Moderate | | Short | | Outage | |
| | Environmental conditions | Severe | Mild | Severe | Mild | Severe | Mild | Severe | Mild | Severe | Mild | Severe | Mild | Severe | Mild | Severe | Mild |
| Condition monitoring tasks | Vibration monitoring | | | | 4/16 | | 8 | | | | 12 | 16/26/52 | 0/16/24 | 0/26 | 0/8/12/16/26/52 | | 0/104 |
| | Performance monitoring | | | | | | | | | | | | | | | | |
| | Thermography | | | | | | | | | | | | | | | | |
| | Checking of leakages and fastenings | | | | 0/12 | | | | | | | 0/12 | 0/12 | 0/12 | 0/12 | 0/12 | |
| | Functional testing during operation | | | | 0/16 | | 4 | | | | | 16 | 16/24 | 0/16 | 0/4/12/16/52 | 0/52 | |
| | Functional testing during outage | | | | 52 | | 52 | | | | 0/104 | | | | 0/52 | | 0/52 |
| | Four Year period Functional testing | | | | 208 | | | | | | | | | | | | |
| Preventive maintenance tasks | Pump overhaul | | | | | | | | | | | | | | | | |
| | Inspection of supporting structures | | | | | | | | | | | | | | 0/416 | | |
| | Casing NDT inspection | | | | | | | | | | | | | | | | |
| | Bearing greasing | | | | 16/26/52 | | 104 | | | | 12/26/52 | 26/52 | 0/16/24/104 | 26/52/104 | 0/13/16/26/52/104 | 52 | 52/104 |
| | Coupling inspection | | | | | | | | | | | | | | 0/104 | | |
| | Replacement of coupling elements | | | | | | | | | | | | | | 0/312 | | |
| | Inspection of logic control | | | | 104 | | 104 | | | | 104 | | | | 0/104 | | |

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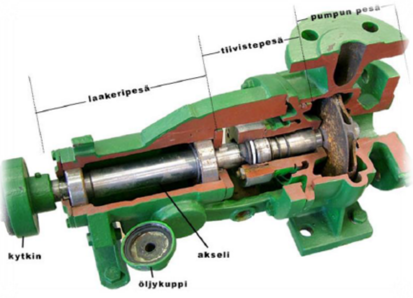
## **Case 2:** Optimized Grease Lubrication Task for Centrifugal Pumps

2 3

- Grease lubrication was optimized by utilizing special software to calculate re-lubrication intervals and amount of grease
- Calculation is based on
  - Bearing type
  - Bearing diameters
  - Bearing operating temperature
  - Bearing load
  - Rotational speed
  - Operating time
- Optimal greasing interval is calculated with 10% failure probability






## **Case 2:** Optimized Grease Lubrication Task for Centrifugal Pumps - Results

2 3

| Location | Equipment type | Bearing type | Bearing measurements D, d, B (mm) | Bearing temperature (°C) | Rpm (1/min) | $C/P_u$ Load level Low=(L) Moderate=(M) High=(H) Very high=(V) | Operating hours per year | Current frequency (weeks) | Optimized frequency (weeks) |
|---|---|---|---|---|---|---|---|---|---|
| 10TR30D0010 | K-KESKIPAKOPUMPPU | 2206A, 6305 | 62, 25, 17 62, 30, 20 | 50 | 1420 | 47,8 (L) 68 (L) | 1500 | 26 | 520 |
| 10UH37D0003 | K-KESKIPAKOPUMPPU | 6305-Z, 2206K | 62, 25, 17 62, 30, 20 | 50 | 2880 | 47,6 (L), 10 (L) | 1500 | 26 | 520 |
| 10UH91D0001 | K-KESKIPAKOPUMPPU | 6305-Z, 2206K | 62, 25, 17 62, 30, 20 | 50 | 2880 | 47,6 (L), 10 (L) | 1500 | 26 | 520 |
| 20UH01D0001 | K-KESKIPAKOPUMPPU | 7308B | 90, 40, 23 | 50 | 2900 | 36,5 (L) | 1500 | 26 | 260 |
| 20UH01D0002 | K-KESKIPAKOPUMPPU | 7308B | 90, 40, 23 | 50 | 2900 | 36,5 (L) | 1500 | 26 | 260 |

**Main results:**

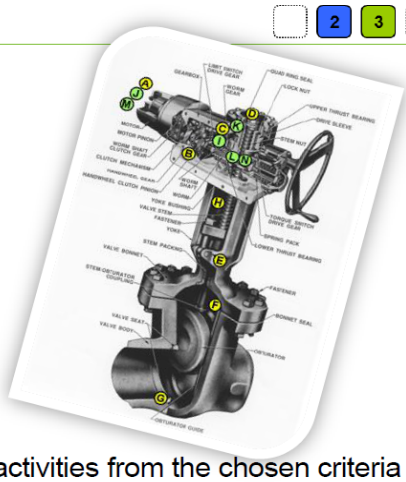
- **Greasing frequency were increased for 251 equipment**
  - **Class 2: 44 pcs.**
  - **Class 3: 207 pcs.**
- **Unchanged greasing frequency for 71 equipment**
  - **Class 2: 31 pcs.**
  - **Class 3: 40 pcs.**
- **Savings ~ 1 FTE**

Case 3 shows how to optimize maintenance task for motor operated valve´s actuators by using simplified streamlined RCM–flow chart.

## **Case 3:** Optimized Maintenance Tasks for Actuators of Motor Operated Valves

2 3

- Maintenance optimization was based on
  - Equipment type
  - Safety class
  - Equipment class
  - Service condition
  - Duty cycle
  - Risk effect
  - Maintenance and operation experience



- A flow chart was made to define maintenance activities from the chosen criteria

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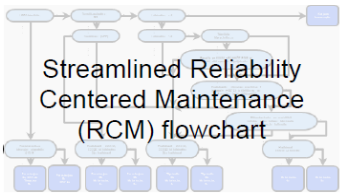
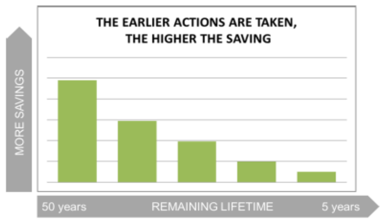
## **Case 3:** Optimised Maintenance Tasks for Actuators of Motor Operated Valves

2 3

Demand for further savings and actions to allocate resources in Loviisa Nuclear Power Plant.

- Maintenance optimization of actuators of motor operated valves by developed streamlined RCM flowchart during 2008
- Criteria based on plant risk, equipment type and operational conditions
  - ➢ Over 700 periodic overhauls replaced with periodic inspections
  - ➢ Less work in yearly outages –> cost savings
  - ➢ Reduction of 3 FTE
  - ➢ **0,25 M€/year savings**
- More optimization of maintenance periods during 2014
- Optimization based on maintenance history as found and as left condition evaluation
  - ➢ Earlier actions are made the higher potential for cost savings -> 10 years of delay would have reduced benefits 50%

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Case 4 shows how to optimize reactor containment's isolation valves leak test frequencies by using PSA risk importance and maintenance history.

## **Case 4:** Optimization of Reactor Containment Isolation Valves Leak Test

2

- The objective is to optimize leak tests frequency based on the valves risk importance and maintenance history
- Risk importance is defined by PRA
- Current leak test frequency was one year for all isolation valves
- Valves which has risk importance will be leak tested every year and other valves will be tested based on maintenance history as follows:
  - No repair works for the valve in last four years → leak test frequency is 2 years
  - No repair works for the valve in last eight years → leak test frequency is 4 years
  - If the valve does not pass the leak test → frequency is returned back to one year
- Results:
- Based on risk importance 98 valves are tested annually
  - LO1 49 pcs.
  - LO2 49 pcs.
- 313 valves are tested based on the maintenance history
  - LO1 147 pcs.
  - LO2 166 pcs.
  - Approx. 2/3 (>200) valves test frequency is more than once per year

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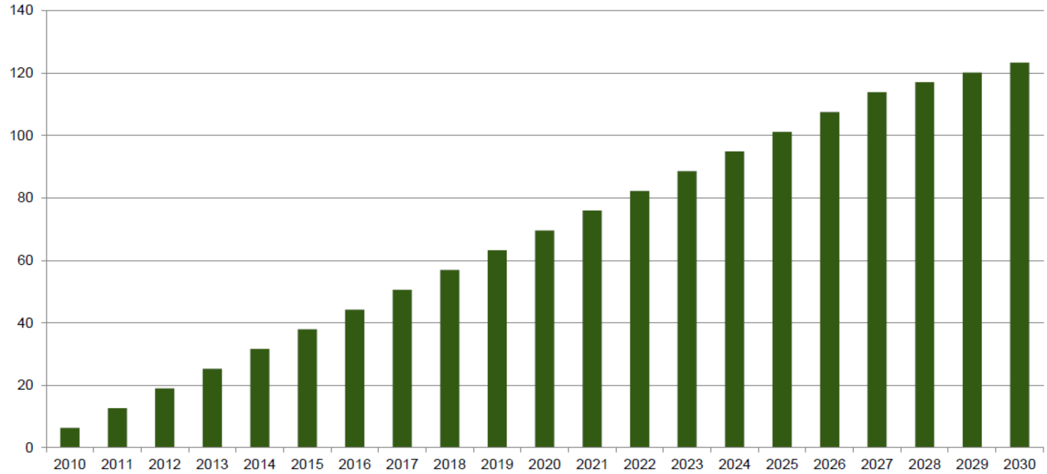
## **Case 4:** Benefits of the optimization of Reactor Containment Isolation Valves Leak Test

2

Cumulative dose reduction [manmSv]

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Case 5 shows how to optimize maintenance task for electrical motors by using simplified streamlined RCM–flow chart.

## Case 5: Optimization of maintenance program for electrical motors

2 3

- Maintenance optimization was based on
  - Equipment type
  - Equipment class
  - Duty cycle
  - Risk effect
  - Maintenance and operation experience
- A flow chart was made to define maintenance activities based on the chosen criteria

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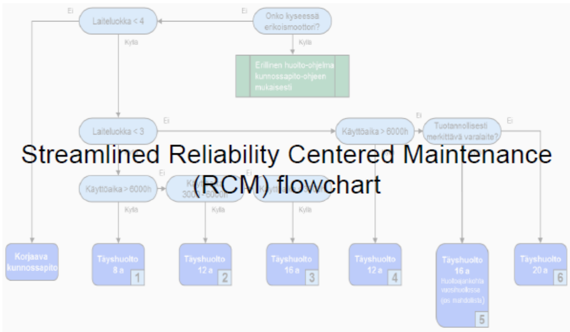
## Case 5: Optimization of maintenance program for electrical motors

2 3

**Main result:**

- **All motors periodic maintenance tasks were synchronized based on flowchart diagram**
- **Non-critical motor overhaul periods increased**
- **Resource allocation to most important works**

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Case 6 shows how to optimize rotating equipment´s vibration measurement frequencies by using criticality class, duty cycle and operating conditions of equipment.

## Case 6: Optimization of the rotating equipment's vibration measurement frequencies

1 2 3

- Vibration measurement frequency matrix was created for criticality class 1-3 equipment
- Frequencies are based on:
  - Operating conditions
  - Criticality Class
  - Duty cycle

**Main results:**
- **Vibration measurements for the safety systems were synchronized with surveillance programme**
- **Vibration measurement frequency was increased for the short duty cycle equipment**

| Criticality class | Duty cycle (h/a) | Operating conditions | Frequency ± 30% |
|---|---|---|---|
| 1 | > 6 000 | Bad | A + E |
| | | Good | A + E |
| | 3 000 – 6 000 | Bad | C |
| | | Good | C |
| | 500-3000 | Bad | E |
| | | Good | E |
| | < 500 | Bad | G |
| | | Good | G |
| 2 | > 6 000 | Bad | B or A + E |
| | | Good | B |
| | 3 000 – 6 000 | Bad | E |
| | | Good | E |
| | 500-3000 | Bad | G |
| | | Good | G |
| | < 500 | Bad | G |
| | | Good | G |
| | Safety systems | | Integrated with surveillance |

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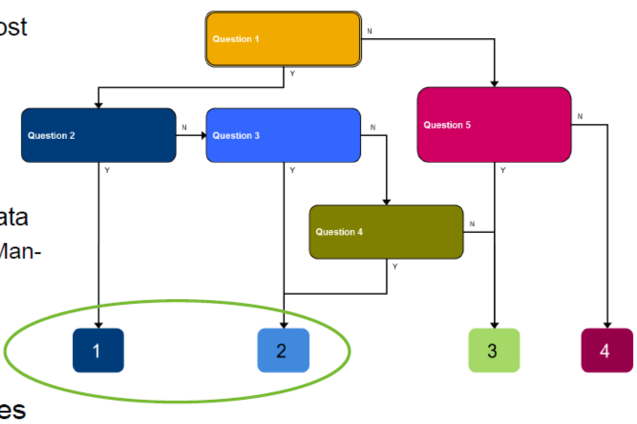
Basis of full scope RCM analysis performed in Loviisa Power Plant.

## RCM-analysis in Loviisa

- RCM analysis will be done to the most critical equipment's where are great potential to optimize maintenance cost and improve availability and safety
- Analysis software used in Loviisa is ELMAS (**E**vent **L**ogic **M**odeling and **A**nalysis **S**oftware)
- RCM analysis utilizes lots of plant data
  - Failures, PM's, Modifications, costs, Man-hours
  - Unavailability, (MTTR, MTBF)
  - Process parameters
  - Ageing and failure mechanisms
- Successful RCM analysis requires very good plant wide co-operation

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Case 7 shows main results of full scope RCM analysis for main seawater pumps and motors.

2

## **Case 7:** RCM analysis for Main Seawater Pumps and motors

- Maintenance KPI's  was showing significant potential to reduce maintenance costs of main seawater pumps and motors. There was doubt that current maintenance program was not optimized.
- Results:
  – Cost-benefit ratio for 6 years overhaul period is 7 % better than current 4 years period
  – Cost-benefit ratio for 8 years overhaul period is 8,5 % better than current 4 years period
- Based on RCM analysis Seawater pumps and motors overhaul period was increased from 4 to 6 years. Even 8 year period is possible but decision was to get experience from 6 year period first.
- New maintenance program was taken into use 2013

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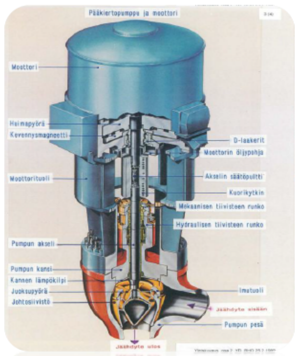
Case 8 shows main results of full scope RCM analysis for primary circulating pumps and motors.

1

## **Case 8:** RCM analysis for Primary Circulation Pumps (PCP)

- Maintenance KPI's  was showing significant potential to reduce maintenance costs and reworks of PCP's. There was doubt that current maintenance program was not optimized. Current overhaul period for PCP is 3 years and motor 6 years
- Most significant causes for unplanned maintenance costs was reworks made during the pump overhaul. Pump structure is very complicated and there is risk for human error all the time when overhaul is done
- Goal is to increase PCP's overhaul period to 6 years and synchronize pump and motor overhauls
- Results shows that it is possible to increase overhaul period from 3 to 6 years, without increasing the plant risks (unavailability/production loss and safety)
- 20a simulation period provides > 99 % availability for 6 a overhaul period
- In 2013 outage has been analyzed pumps condition which have been operating 1, 3 and 4 years
- Overhaul period will be changed after one critical component cracking problem is solved

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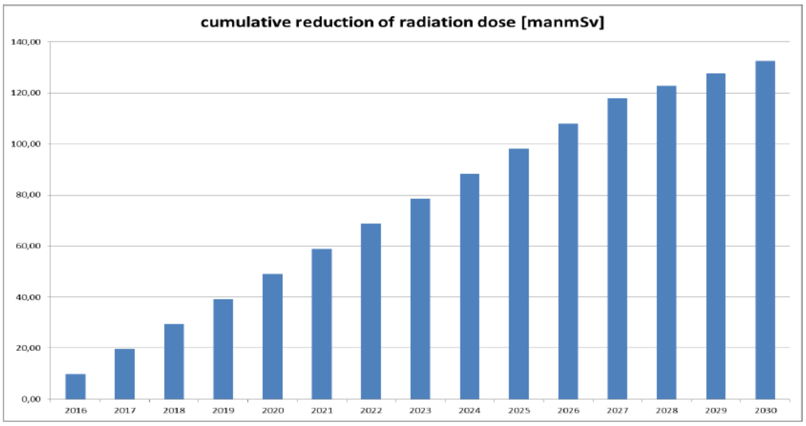
## **Case 8:** RCM analysis for Primary Circulation Pumps (PCP)




Based on RCM analyses (LO1-K323-00218) the change overhaul period of the pump from three years to six years the functional failure risk of the pump decreases by 25%.

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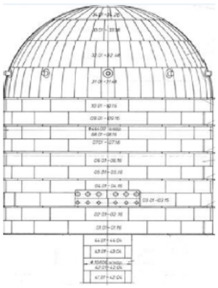
Case 9 shows main results of full scope RCM analysis for steel containment leakage test interval change from 4 years to 8 years.

## **Case 9:** Steel containment leakage test interval change from 4 to 8 years

- Maintenance KPI's and experience was showing significant potential to reduce overall plant risk and outage duration by increasing containment leakage test intervals.
- In addition ANSI standards allows to use more than 4 years intervals based on the history and results of leakage tests
- Leakage interval change was justified based on:
  - RCM analysis
  - PRA analysis
  - Analysis of containment lifetime and aging phenomenon's
  - Leakage test results and maintenance history



Results:

- Reduction of outage critical path by 36 hours
- Plant risk induced by the leakage test is reduced by 70% due to reduction of human error risks during the test (LO1-K216-00090).

New intervals will be taken to use in outages 2016.

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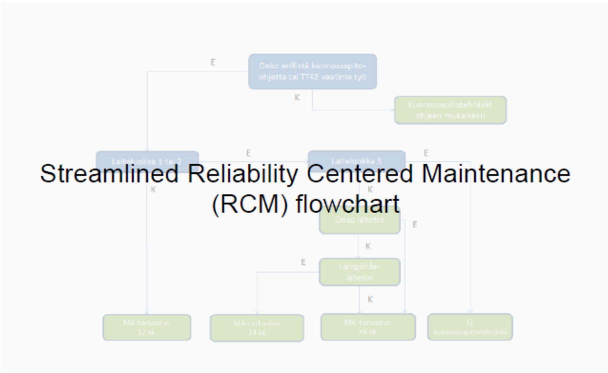
Case 10 shows how to optimize maintenance task for I & C equipment's by using simplified streamlined RCM–flow chart.

## Case 10: I&C maintenance tasks optimization

- I&C equipment backlog in criticality class 3 has increased strongly in recent years
- Detailed analyzes showed that maintenance tasks frequencies were not optimal
- Streamlined Reliability Centered Maintenance flowchart was developed to define optimal frequency of I&C maintenance tasks
- New flow chart will be taken in use in 2015

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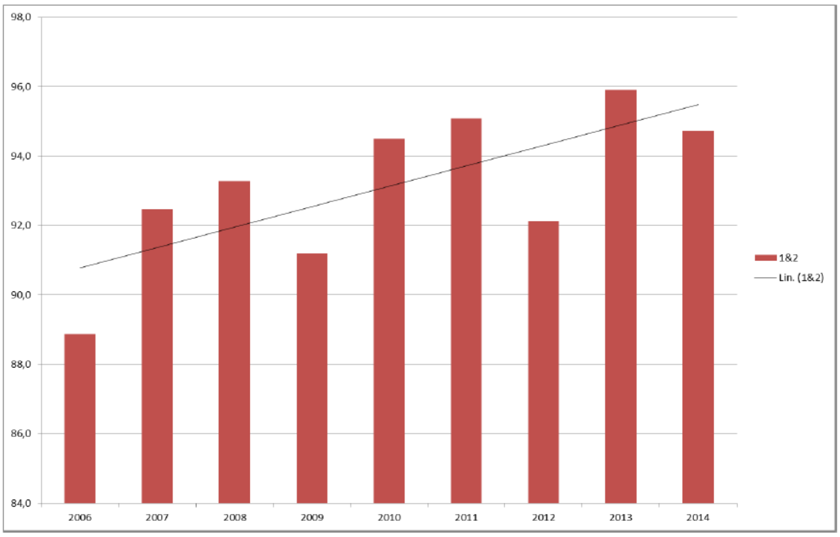
Slides below shows how successful maintenance optimization affects to on–time delivery and maintenance backlog of the most critical equipment.

## On-time delivery in criticality classes 1 & 2

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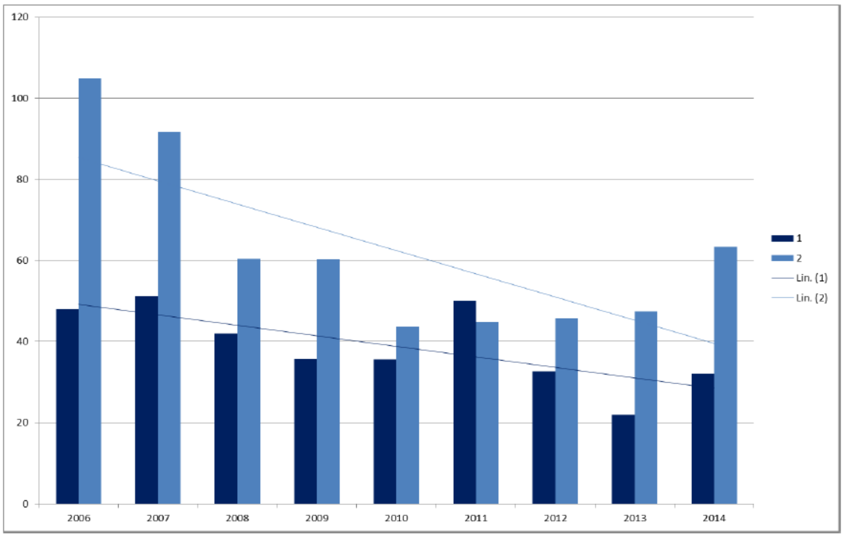
# Average Backlog of equipment in Criticality classes 1&2



## ANNEX II.
## METHODS FOR OPTIMIZING NON–CRITICAL COMPONENT MAINTENANCE STRATEGIES

***EPRI Case Study***

Martin Luther BRIDGES, P.E.

Electric Power Research Institute
UNITED STATES OF AMERICA

**Summary**

Once the time consuming work of classifying SSC as to their functional importance, it is necessary to take steps to assure the maintenance strategies that are devised for the components are appropriate for the functional importance of the component. Many times, SSC are classified into the various levels of functional importance, but the processes that are used to monitor, assess and restore the SSC have little discrimination between the various classifications. This lack of meaningful discrimination can negate any potential savings that could have resulted from the classification effort.

Since a lot of work has been done to maximize the reliability of critical components and regulatory and code requirements limit the amount of adjusting that can be done to the strategy for these SSC, most efforts in the recent past have focused on non–critical SSC. Recognizing this, the Maintenance Working Group and the Equipment Reliability Working Group working with EPRI, developed a method that can be used to optimize the maintenance strategy for non–critical equipment. This methodology is discussed in the following case history.

## II-1. INTRODUCTION

Once SSC have been classified based on their functional importance, it is important to develop a maintenance strategy for these components that is appropriate for their classification. It is important at this time to remember that non–critical SSC by their very definition have been determined to be SSC that can experience an occasional failure with little or no consequence to the safe operation of the plant. If, as a result of one last review of the component's functions, it is determined that no failure can be tolerated, this SSC should be reclassified as 'Critical'.

When developing the maintenance strategy, there are several ways to approach the development of the strategy. One method would be to start with the current PM strategy and evaluate the impact of eliminating some tasks, extending the intervals of other tasks, and making no changes to other tasks. This can be considered as optimization by subtraction. A second method is to start with an 'empty plate' and assign PM tasks based on the identified failures and failure modes that are specific to the SSC in its current application, service environment and duty cycle. This is considered as optimization by addition. Both of these methods are discussed below.

## II-2. OPTIMIZE BY SUBTRACTION

Starting with the current maintenance strategy takes advantage of the performance of the SSC which was deemed to be 'Satisfactory' in the preparatory evaluation. However, this method also has the potential of not identifying the failure modes that the PM program is designed to address, thus not providing needed information that will be helpful in optimizing the maintenance strategy.

Begin the process by assembling the work orders, action requests and corrective action reports that make up the history of the SSC since it was last overhauled. This history should include all corrective maintenance, all preventive maintenance and any condition based maintenance evaluations including vibration spectra, oil analysis reports, information in the data historian files, and information from operator rounds. It should also include all recommendations from the expert panel or health committee that provides oversight of the components in the plant if such a group exists.

Review the as–found information that was recorded by the maintenance personnel during the last major intrusive maintenance task like a refurbishment. This review should focus on the parts that were found to be in ‘like new’ condition and on those parts that were identified as being as or near failure. It may be necessary to talk with the maintenance technicians to get additional information. A well scoped and timed refurbishment should be designed to replace those parts that are almost at the point of failure and the timing should be such that they have not failed. Repeat this review for each intrusive task. In many cases this review may have been done as part of the post maintenance assessment of the work.

For the parts that are considered to be ‘failed’, review the CM and PdM tasks that are being performed to determine if these tasks had detected the advanced degradation. If it is determined that they did not identify that the parts were in an advance state of degradation, the task should be considered as not effective in identifying the advanced degradation. This task should be marked for further evaluation. The areas that should be evaluated include the scope of the task, the training of the technicians performing the tasks, and the task intervals. Parts that are ‘like new’ represent items that do not need replacement at this time and the scope of the maintenance task should be adjusted so that they are only replaced when necessary. The results of these evaluations should be used to optimize the maintenance strategy for the SSC.

Review the identified failure modes for this SSC and identify any failure modes that have trendable degradation that can be monitored in lieu of the intrusive maintenance. Make sure that the monitoring tasks are included in the PM plan for the SSC. A danger in this approach is that the absence of identified failures or advanced degradation can often be interpreted as the result of an unnecessary task or a too frequent interval. The real answer may in fact be that the reason for the lack of failure or advanced degradation is a well–designed maintenance strategy. When possible, review the operating experiences of similar components at other NPPs for their experience and factor this experience into the evaluation.

Using the results of the evaluations, begin the elimination of any PM task that requires that the component be taken out of service and declared ‘Unavailable’. Probabilistic safety evaluations consider equipment unavailable whether the equipment is in a failed state or is out of service for PM. Therefore, unavailability due to the SSC being failed is not considered any different than unavailability due to PM. The functional importance evaluation has already determined that some level of failure can be tolerated for this SSC. Therefore, if restoration of degraded parts can be accomplished in the same or less time than is required for the PM, elimination of the PM should be considered. This distinction creates the potential to focus the maintenance strategy on managing the degradation of key parts of the SSC and using condition based maintenance to schedule restoration maintenance for degraded parts as required rather than scheduling time based maintenance tasks.

If known failure modes and degradations are detected by multiple maintenance tasks, consideration should be given to eliminating one of the tasks. When considering the maintenance strategy for non–critical SSC, the philosophy of adequate protection suggests that any optimization of the maintenance strategy for non–critical equipment include evaluations of how much monitoring of the progression of degradation mechanisms is enough. The answer to the question for critical SSC is clearly that all reasonable efforts should be made to preclude failure. For non–critical SSC, the answer is less obvious and is dependant more on the risk aversion culture of the evaluating Member State. As part of the optimization, eliminate completely any maintenance task that provides duplicate detection or protection from a specific degradation mechanism. Care should be taken to not delete tasks that provide detection or protection for multiple failure mechanisms unless it is determined the unprotected failure modes are not significant.

Once the individual tasks have been evaluated, create a list of all of the tasks that remain associated with the SSC and list the task interval for each task. Review the list for reasonableness and conflicts. Look for tasks that duplicate inspections and evaluations and look for intervals that conflict with each other, such as an inspection that occurs at the same time the SSC is being overhauled. Make any necessary adjustments to task content or to task intervals. Once this review is complete, there will now be a 'new' maintenance strategy for the SSC that is reflective of its functional importance classification of 'non–critical'.

## II-3. OPTIMIZATION BY ADDITION

An alternative approach for establishing the optimum PM strategy for a non–critical component would be to design a minimum maintenance program, and then add additional tasks to provide mitigation of known failure modes that are not properly covered by the minimum program. This approach avoids the trap of biasing the choices of tasks or intervals. This approach also allows the strategy to be developed based on the specific failure modes that are being addressed.

Start by reviewing the identified failure locations for the SSC. These can be found in vendor manuals, textbooks or maintenance guidelines for the SSC. For each failure mode, list the maintenance task or the CM task that can help monitor the failure mechanism so that action can be taken to perform restorative maintenance before a failure occurs. These failure locations can be found by reviewing the vendor drawings of the SSC, reviewing the work history, or using a software tool such as the EPRI Preventive Maintenance Basis Database, Rolls Royce ER Dashboard or ABB Ventyx IQ Review.

Figure II-1 is from the EPRI Preventive Maintenance Basis Database (PMBD) for Multi–stage, Horizontal Barrel Pumps.

| | |
|---|---|
| **Failure Location:** | Balancing Device |
| **Degradation Mechanism:** | Wear |
| **Degradation Influence:** | Distortion due to improper pump startup |
| **Discovery or Prevention Opportunity:** | Thrust bearing temperature<br>Balance line leakoff pressure or flow<br>Vibration<br>Inspection |
| **Time Code:** | R |

**Failure Location**

Automatic Oilers
Balancing Device
Bearing Oil Slinger Ring
Bearing Seals - Labrynth
Bearing Temperature RTD's
Bearings - Antifriction (radial and thrust)
Bearings - Kingsbury type
Bearings - Sleeve
Breather Caps & Sight Glass Vents
Connections & Piping
Diffusers, Volutes & Channel Rings
Discharge and Suction Flanges
Gaskets & O-Ring
Impellers
Lube Oil
Lube Oil Cooling Heat Exchanger or Internal Bearing Cooler
Lube Oil Metering Orifice
Lube Oil System
Pump Base Plate and Foundation
Pump Casing and Closure Head
Seal - Mechanical
Seal - Packing
Shaft
Stuffing Box Flange to Horizontal Joint
Wear Rings and surfaces

*FIG. II-1. Screen shot of the EPRI Preventive Maintenance Basis Database*

Using this list, eliminate any locations that do not cause ‘fatal’ failures, e.g. failures that would cause the SSC to lose its ability to perform its design function. If a failure location causes degradation, but the component can still meet its intended function until corrective maintenance can be performed, this would fit very well with the intended definition of a non–critical SSC. Using the list of remaining failure locations, list the maintenance tasks that can be used to manage the degradation of the SSC. This list will now be the starting point for the maintenance strategy for the SSC.

Next, review the estimated time from the discovery of the degradation until the degradation has progressed to a functional failure. Depending on the risk tolerance level of the organization and the applicable regulatory agency, establish an interval for performing the maintenance that provides sufficient time to correct the degradation before the functional failure occurs. For plants that have a long operating history or for plants that are representative of a group of plants that have a long maintenance history, this interval can be well defined by analysing the history of all of the similar SSC. Using this history to assign an interval based on the historical performance of the components will create a task that looks like ‘time based’ maintenance when in fact it is condition based maintenance that takes advantage of many assessments of SSC condition.

Once the list of tasks has been created and the intervals have been defined and added to the table, this table can be used as the maintenance template for the subject non–critical SSC.

## II-4. EXPECTATIONS

Once the maintenance strategies for the list of non–critical SSC has been developed, it will be necessary to implement a change management program to educate the management team and the rest of the plant staff on the appropriate expectations for the performance of the non–critical SSC. Non–critical SSC should have different expectations than critical components. The corrective action program also needs to be in alignment with these standards to prevent excessive investigations. Changes and deferrals to non–critical PMs should not require the same level of review as changes to critical PMs, but the process and expectations for these reviews should be clearly documented.

The first step is to inform and emphasize that SSC that have been classified as non–critical can fail without causing an unacceptable risk to the health and safety of the plant staff or the public. This should be first discussed on the generic level, and then on the specific SSC level. It is important that there is uniform agreement on this fact from all levels of management, operation and any regulatory bodies that will be reviewing plant records and evaluating any failures. It is also important that the management team issue the appropriate statements and directives that show they agree with this idea and that corporate, plant and personnel goals will be monitored based on this philosophy.

Once this change management process is being communicated, plant processes and procedures should be revised to reflect these goals. Particular care should be taken that the corrective action program and the continuing improvement program be adjusted to apply actions that reflect the revised classifications of the SSC. For example, the Root Cause Analysis method is an appropriate response to the failure of a critical SSC while the Apparent Cause Evaluation method is more appropriate for non–critical SSC.

Finally, it is important that the entire SSC classification process be a living program. The classification of SSC should be reviewed as part of each failure evaluation, as part of the work scheduling process for the performance of the maintenance strategy, and any time a modification or other plant change is made that affects the SSC.

## II-5. CONCLUSION

With several tens of thousands or maybe even hundreds of thousands of SSC in a nuclear power plant, depending on how SSC are counted, having a coherent and adequate maintenance strategy is an ongoing challenge. It is important to assure that the right work is done on the right equipment at the right time so that equipment reliability can be maintained at a reasonable cost. This can be done with a high level of effectiveness is SSC are classified based on their functional importance and the appropriate level of maintenance and monitoring are done.

Equally important is the need to assure that the expectation of the regulator, management, and plant staff are established to reflect the implementation of the classification process. The establishing of the expectations and the implementing and internalizing of the change management plan are the key to the success of the program.

ANNEX III.
# METHODOLOGY OF THE MAINTENANCE STRATEGY AT PAKS NPP

***PAKS Case Study***

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**Summary**

This case study is based on the new maintenance optimization process of Paks NPP Hungary. In Paks there are 4 VVER (PWR) units, each have 500 MWe electric power output. Their average age is approximately 30 years and in general the applied maintenance strategy is based on the original vendor's recommendations. These are the 'run-to-failure' and/or cyclic preventive maintenance. The applied strategies are basically based on the safety classification of the equipment and on the equipment importance to the production of electric energy. This case study presents a new approach of optimizing the maintenance programme at Paks NPP focusing more on using condition monitoring, and condition based maintenance. The presented classification methodology is based on reliability centred maintenance analysis and includes application of risk matrix as well.

## III-1. INTRODUCTION

### III-1.1. System scoping

The first task was determining the scope of the new maintenance strategy. The selected systems are systems related or important to the safety and the production. In a pilot project the introduction of the methodology started with two systems for the modelling. These are the low pressure safety injection system and the volume and chemistry control system.

### III-1.2. Implementation

The intention of the Paks NPP is to extend this methodology to all plant technological systems. The scoping phases are the following:

(1) Two systems selected for developing and checking/benchmarking the methodology as mentioned above;

(2) Five selected systems that are covered in the on–line maintenance scope:
   (a) Diesel generators;
   (b) Essential service water system;
   (c) High pressure safety injection system;
   (d) Containment spray system;
   (e) Safety component cooling system;

(3) 15 selected systems, these are included in scope of the maintenance rule:
   (a) Auxiliary feedwater system;

(b) Component cooling system;
(c) Containment isolation system;
(d) Containment spray system;
(e) Demineralized water system;
(f) Diesel generators system;
(g) Essential service water system;
(h) Feedwater system;
(i) High concentration boric acid system;
(j) High Pressure Safety Injection system;
(k) Hydro–accumulator system;
(l) Main steam system;
(m) Primary overpressure protection, safety and relief valves;
(n) Reactor protection system;
(o) Residual heat removal system;
(p) Safety electric supply system;
(q) Emergency feedwater system;
(r) Steam generator (SG) blowdown system;
(s) Spent fuel cooling system;
(t) Turbine isolation valves.

## III-2. MAINTENANCE STRATEGIES AND DEFINITIONS

The applied maintenance strategies are based on the primary function of the equipment, which are the following:

- Corrective maintenance (run–to–failure);
- Preventive maintenance:
  - Cyclic maintenance;
  - Condition based maintenance.

### III-2.1. Run to failure

The functional failure of the equipment does not have significant nuclear or economic risk. The corrective maintenance is initiated by the failure of the equipment.

### III-2.2. Preventive maintenance

Preventive maintenance can be cyclic (independently of its condition) and condition based (using the primary function monitoring).

#### *III-2.2.1. Cyclic maintenance*

The maintenance cycle of the equipment is predefined. The cycle can be fixed or flexible cycle. The cyclic maintenance includes also the CM test of the equipment function.

#### *III-2.2.2. Condition based maintenance*

The condition based maintenance can be time and/or parameter controlled. The parameter controlled maintenance is based on the primary function monitoring; this can be e.g. pressure difference and flow rate of the pump, stroke time and/or leakage rate of the valve. These parameters are key performance indicators as defined based on the ASME OM[1] code.

During the reactor operation there are two groups:

- Condition based maintenance during power operation;
- Condition based maintenance during cold shut down.

### III-2.3. Run–To–Failure

In this group there is equipment which has no impact for the nuclear safety or electric performance or its failure not causes large economic problems.

The maintenance classification focuses only on active equipment, like valves and pumps. Passive elements and components like pipeline, tanks, heat exchangers, filters, etc. are not in the scope.

### III-2.4. The objective of the classifications

The aim of the equipment grouping is to declare unique object for the classification. The elements of the groups should have the same primary function, e.g. pumps with special safety functions. These groups are evaluated using the risk matrix, and it results in identification of the risk importance of the group dividing the groups to critical or non–critical equipment groups. The categorization used only for the active components.

### III-2.5. Analysis of the Function of the equipment groups

The classification starts with the identification of the function of the equipment group, e.g. nuclear safety and/or electric production functions. This will be input information to the risk matrix. Functional failures are based on the PSA failure modes, e.g. pump fails to start.

### III-2.6. The risk matrix

The main goal of the risk matrix is to separate the critical and non–critical equipment groups. The risk matrix is based on the application of the following Table III–1.

TABLE III–1. RISK MATRIX

| | | | | | |
|---|---|---|---|---|---|
| CONSEQUENCE | Serious consequence | Low risk | Medium risk | High risk | High risk |
| | Medium consequence | Risk–free | Low risk | Medium risk | High risk |
| | Negligible consequence | Risk–free | Risk–free | Low risk | Medium risk |
| | Without consequence | Risk–free | Risk–free | Risk–free | Low risk |
| | | Never | Low frequency | Medium frequency | Frequent |
| | FREQUENCY | | | | |

#### *III-2.6.1. Risk levels*

The result of the risk classification is to separate the critical and non–critical components. If the equipment group is classified to the risk–free category, the group has non–critical components. All the other risk categories mean that the group has critical components.

[1] American Society of Mechanical Engineers Operation and Maintenance Code

The risk levels have the following meanings:

- **High risk** equipment is critical for the nuclear safety and/or the electric production. This equipment should have the maximal reliability; the functional failure of this equipment should be avoided;
- Equipment with **medium risk** has medium impact for the nuclear safety and/or the electric production. The functional failure of this equipment can cause significant economic consequences, loss of production, or degradation of the nuclear safety. The reliability of this equipment  should be kept on high level;
- Equipment with **low risk** has low impact for the nuclear safety and/or the electric production. The functional failure of this equipment can cause insignificant economic consequences, small loss of production, or small incremental nuclear safety risk. These equipment have normal operation control, may run to failure;
- The equipment with **risk free** can use run to failure, the functional failure can not cause any nuclear safety and/or economic damage.

*III-2.6.2.    Determination of the consequences*

The determinations of the consequence are the next point of views:

- Nuclear safety consequences;
- Economic consequences, focused on the electric production;
- Events with serious consequence are the following:
  - The failure causes initiation of the reactor protection system (initiating event), or loss of safety function, or for one or more employees get increased doses;
  - The failure of the equipment causes more than 50 GWh (4 days) loss of production;
- Events with medium consequence are the next:
  - The failure causes one safety train unavailable, or increasing the level of dosimetry for one employee for one day;
  - The failure of the equipment cases between 6 and 50 GWh (12 hour – 4 days) loss of production;
- Events with negligible consequence are the next:
  - Equipment with nuclear safety classification, its failure does not cause the loss of safety train but causes degradation of system reliability; or
  - The failure of the equipment causes between 0,5 and 6 GWh (1–12 hour) loss of production;
- Events without consequence are the next:
  - Equipment have no safety relevance; or
  - The failure of the equipment causes lower than 0,5 GWh loss of production.

*III-2.6.3.    Frequency of the consequences*

The frequencies of the consequences are the following:

- Frequent – when the mean time between failure (MTBF) is smaller than 1 year for these equipment groups;
- Medium frequency – when the MTBF is between one year and 30 years (lifetime of one unit);
- Low frequency – the failure is rarer than once in 30 years;
- Never – the failure never occurred in the industry.

### III-2.7. The process of the maintenance strategy classification

The process of the classification is shown in FIG. III-1.

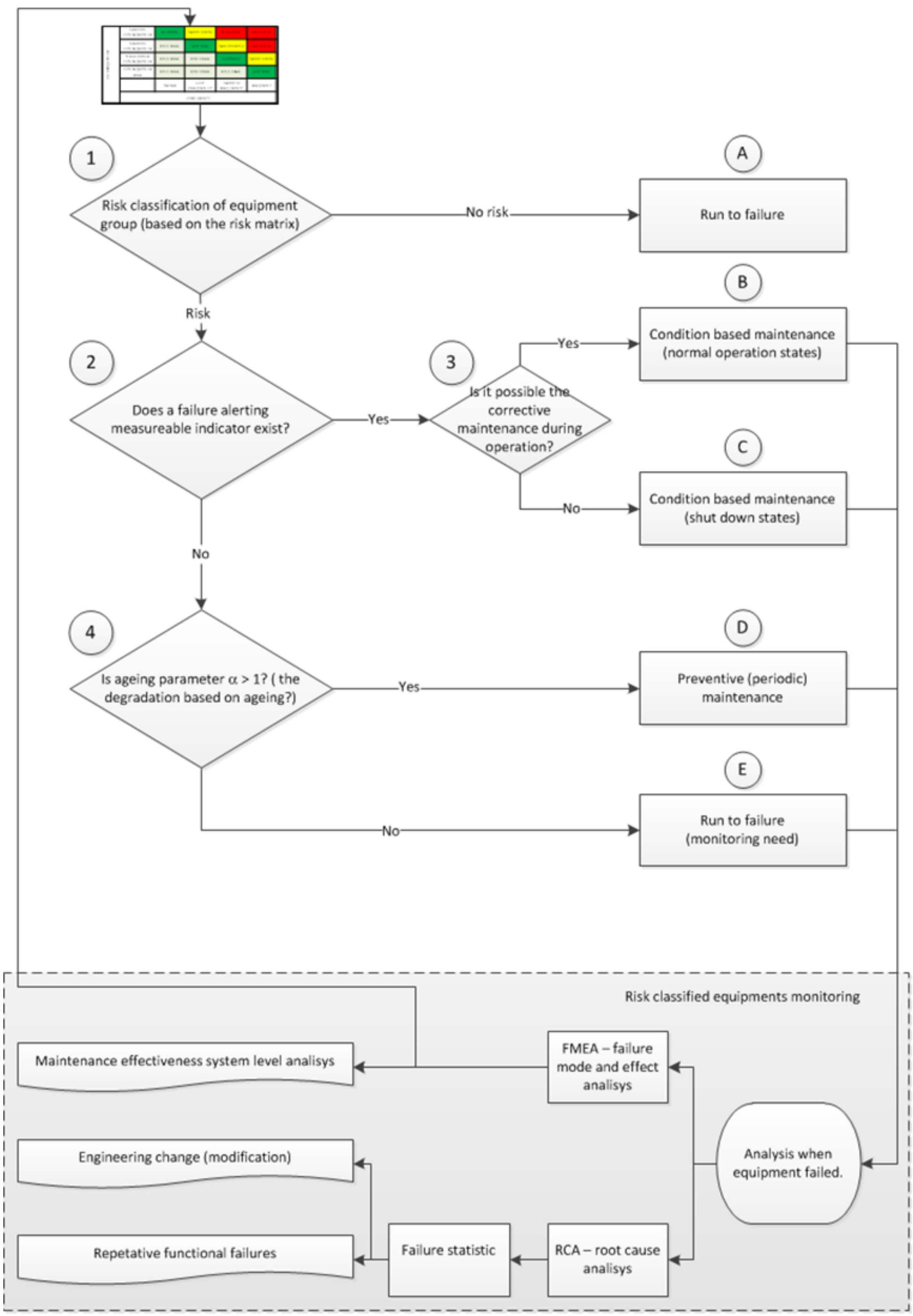


*FIG. III-1. Process of the maintenance strategy classification.*

### III-2.8. Monitoring

The aim of the monitoring is to control the maintenance strategy classification procedure, cyclic feedback to the risk matrix.

The tasks are the followings:

- Analysis when equipment function is failed;
- Failure mode and effect analysis (FMEA);
- Root cause analysis;
- Failure statistics;
- Engineering change (modification);
- Repetitive functional failure;
- Maintenance effectiveness monitoring – system level monitoring.

### III-2.9. Maintenance experiences

This evaluation is done by the equipment engineer. The evaluation is based on the failure events, the operation and maintenance experience, ageing monitoring results, etc. The classification is based on the primary function of the equipment groups, but the secondary functions have to be taken into account as well, e.g. sealing, bearings, etc.

## III-3. IMPLEMENTATION

For the assessments and the categorization the Paks NPP developed a computer programme, and database based on MS Access. It is called ‘maintenance strategy classification’.

## III-4. RESULTS

The results of classification is shown in FIG. III-2:

- Equipment group: volume and chemistry control pumps (primary make up water pumps).
- Maintenance strategy: condition based maintenance.

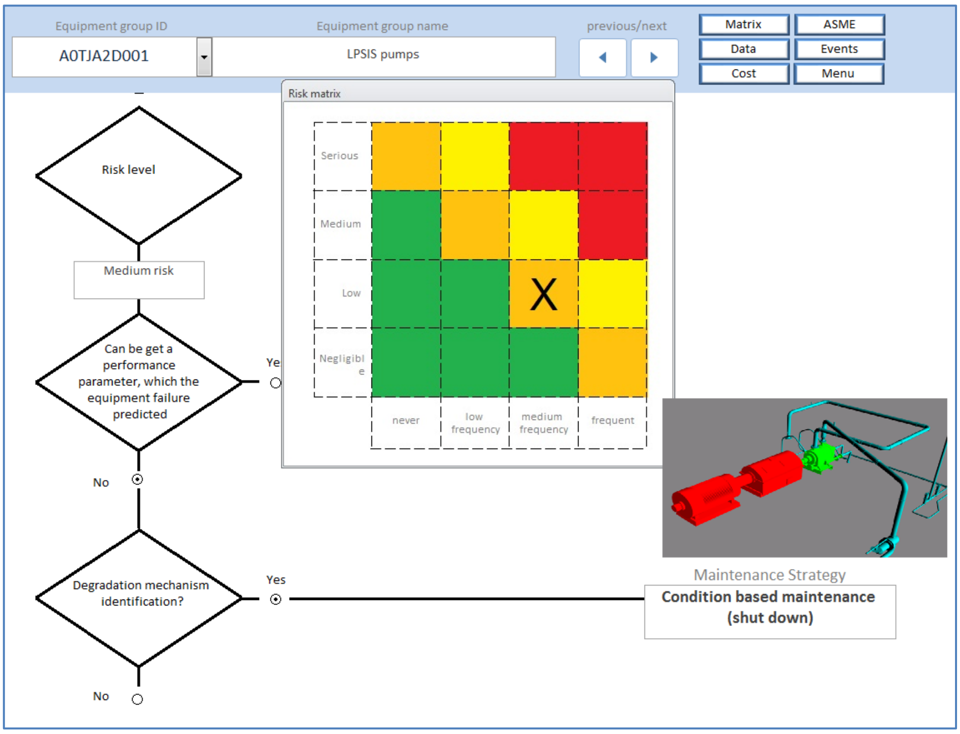


*FIG. III-2. Result of classification of the volume and chemistry control pump.*

ANNEX IV.
# EFFECTIVE MAINTENANCE STRATEGY IN ČEZ NPPS

## *ČEZ Case Study*

Pavel VLČEK

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**Summary**

Effective maintenance programmes established through the ČEZ Effective Maintenance Strategy (EMS) constitute a structured and well documented basis for the equipment reliability system management, establishment of conditions for the implementation of equipment performance and condition monitoring, as well as the regular maintenance cost reduction.
EMS performance is a multi–profession task involving a number of the plant's departments as well as corporate organizations. It includes a plant partition in Technological Systems (TES), TES and TES–equipment categorization, preventive maintenance tasks selection with the use of prepared PM templates, PM tasks comparison with existing PM programme, PM tasks implementation, and a performance of a regular TES condition evaluation and identification of deviations through the System Health Reporting.

## IV-1. INTRODUCTION

The ČEZ Effective Maintenance Strategy (EMS) covers principles and processes to establish effective maintenance programmes for nuclear power plant equipment items based on equipment failure mode analysis, depending on their criticality, working cycles, and conditions. To do this it uses available internal and international information and good practices. EMS is part of the step by step implementation of the reliability system in ČEZ nuclear power plants.

Maintenance programme optimization in ČEZ nuclear power plants aims to achieve the following principal goals through the EMS:

- Regular maintenance cost reduction;
- Establishment of conditions for the implementation of equipment performance and condition monitoring.

At NPP Dukovany, EMS is also an important part of a currently implemented long term operation project, aiming to establish equipment reliability system management with a goal to document plant systems/equipment readiness for operation beyond the plant‘s design service life. This covers:

- Current equipment/system condition evaluation;
- Implementation of service life evaluation and management system based on equipment reliability, performance and CM (health reporting);
- Maintenance programme adjustment.

### IV-1.1. ČEZ organizations involved in the EMS process

Responsibilities, duties and competences are distributed across a number of the plant's departments as well as among the corporate organizations of the ČEZ Company:

- Maintenance – system engineers, component engineers;
- Central engineering – segment engineers;
- Nuclear safety;
- Technical inspection & diagnostics;
- Plant life management & long–term operation;
- Operation modes.

## IV-2. EFFECTIVE MAINTENANCE STRATEGY IMPLEMENTATION PROCESS

The flowchart of an effective maintenance strategy implementation process is shown in FIG. IV-1.

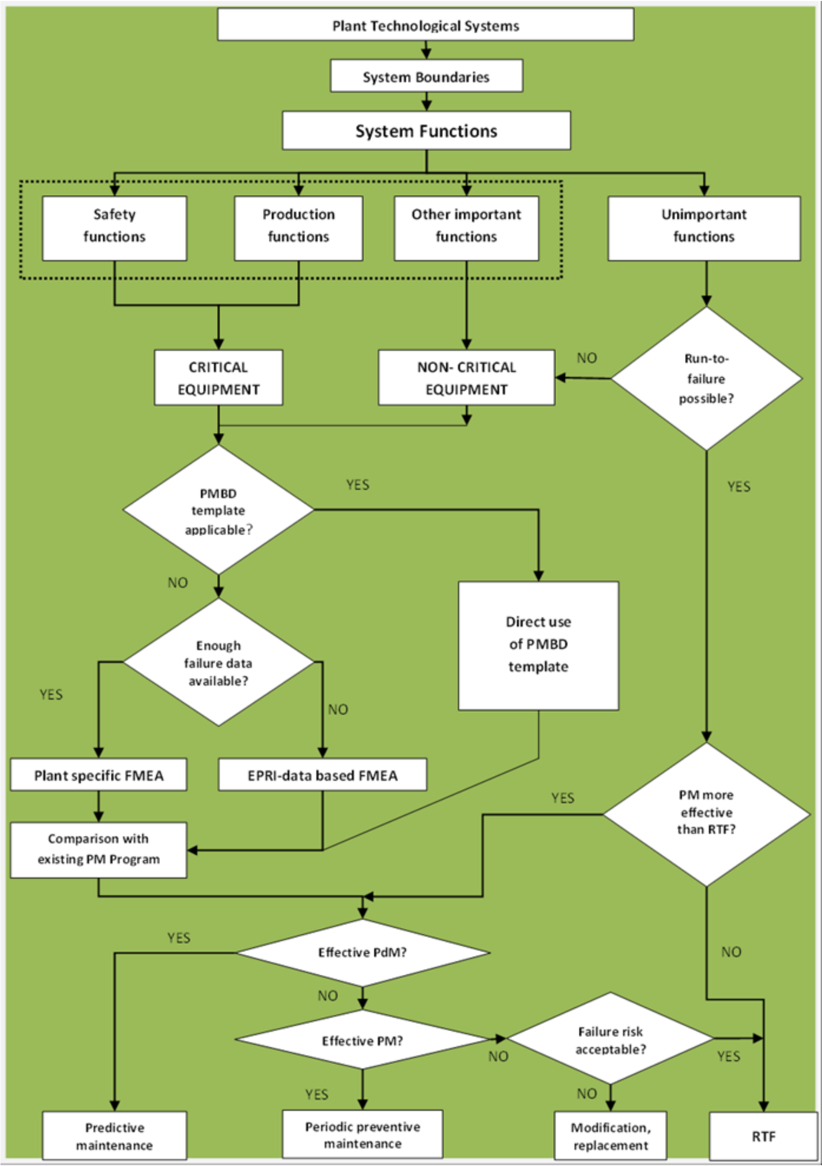



*FIG. IV-1. Effective maintenance strategy implementation process.*

IV-3. PLANT PARTITION IN TECHNOLOGICAL SYSTEMS

- TES boundaries specification;
- TES functions definition;
- TES equipment listing;
- Plant TES division into safety, safety related and other systems.

In total, NPP Dukovany has been divided into 213 TES, of which 98 are safety and safety related systems.

### IV-3.1. Technological systems functions categorization

TES function categories:

- Important functions:
  - Nuclear safety;
  - Operation;
  - Environment;
- Unimportant functions.

TES function's importance criteria:

- Important function criteria – a function is considered important if its loss (either full or partial) results in:
  - Risk of failure to perform a specific category 1 or 2 safety function, or unplanned limiting conditions for operation of technical specifications entries which involve a transition to lower operation modes defined in LCO;
  - Unacceptable impact on the environment outside the plant (serious spillage or leak of pollutants – chemicals, oil, etc. outside the NPP site resulting in a contamination);
  - Immediate impact on the production (unit shut–down, power output reduction ≥ 30%);
  - Production loss (including an outage extension) > 1 day;
- Unimportant function criteria – if a technological function fails to satisfy the above important function criteria than it is considered unimportant.

### IV-3.2. Equipment categorization

Equipment categorization means the equipment examination in light of all TES functions, i.e. each individual component's significance for the TES functions. To make such a categorization, equipment criticality criteria are defined involving importance of functions performed by the equipment and the equipment's failure consequences.

Equipment categories:

Category # 1 – Critical equipment;

Category # 2 – Non–critical equipment;

Category # 3 – Unimportant equipment.

In NPP Dukovany, Category # 1 equipment ratio is about 10%, Category # 2 equipment ratio is about 40%, and Category # 3 equipment ratio is about 50%.

Requirements for maintenance:

- Category # 1 – critical equipment – prevention of all failures:
  – Sub–Category # 1A– equipment with a pre–set service life management programme – ambition to precede failures (non–replaceable equipment);
- Category # 2 – non–critical equipment – elimination of the most risky failure modes, i.e. search for an optimal reliability–maintenance cost efficiency ratio;
- Category # 3 – unimportant equipment – run–to-failure.

### IV-3.3. Equipment category determination process

The flowchart of an equipment categorization process is shown in FIG. IV-2.

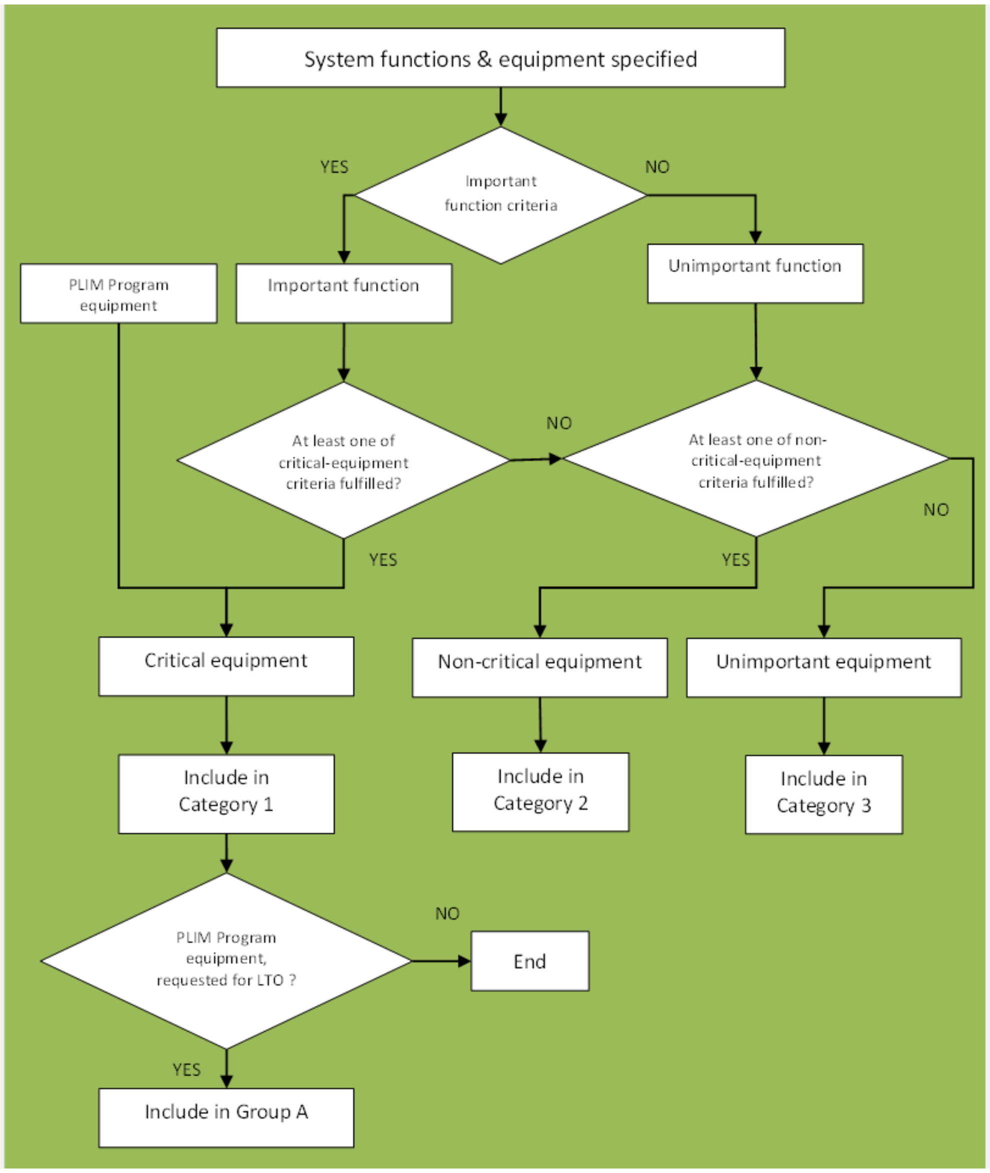



*FIG. IV-2. Equipment category determination process.*

For the critical & non–critical equipment, preventive maintenance tasks are selected with the use of PM templates.

As a basis for the plant's PM template database, the EPRI Preventive Maintenance Basis Database is used in ČEZ NPPs. Where PMBD templates are not available, plant specific PM templates are developed using the company’s internal operational experience; alternatively, plant specific FMEA (Failure Mode and Effect Analysis) is performed to define the PM tasks. If sufficient plant failure data are not available, generic failure data are used. Central engineering segment engineers are responsible for the provision of the plant’s PM templates.

PM template tasks are assigned to individual TES items based on the equipment’s:

- Criticality;
- Working conditions;
- Working cycle.

The assignment results are documented in the criticality tables elaborated for each examined TES (see example FIG. IV-3).

The equipment–specific PM templates are handled as controlled documents within the plant’s document management module, and are linked to equipment records within the equipment register.

IV-4. PM COMPARISON WITH EXISTING PM PROGRAMME

- All PM templates have to be converted to equipment’s PM parameters within the plant maintenance information system;
- Non–use of PM template has to be justified by the relevant system engineers. Such PM parameters will be in the inactive status;
- PM parameters have to cover all activities performed on the equipment (PM template tasks, service–life management programme tasks, legislative requirements and manufacturers’ recommendations). PM parameters will be attributed to the activities;
- Operations–round tasks (routine tasks performed by the operations staff in the course of their regular rounds) will be covered by respective PM Parameters, too. They won’t be realized by means of work orders generated from the PM parameters;
- System engineers comment on the comparison results and document it in the criticality tables (comments on PM extent – see example below FIG. IV-3).

IV-5. TECHNOLOGICAL SYSTEMS FINAL REPORTS

- Description of the system engineer‘s approach to the equipment PM template‘s projection to PM parameters;
- Comparison of existing PM programme with PM templates’ suggestions;
- System engineer‘s suggestion on PM Programme extension or reduction;
- Records from the health report and failure symptoms;
- Annex – Failure–rate analysis (Categories # 1, # 2 only).

The final report is based on the TES criticality table, and is one of the basic documents required by the LTO project.

### IV-5.1. Evaluation of technological system condition and reliability

To assure conformity of the required documentation for operation with actual TES condition, regular evaluation is performed, including an identification of deviations. It serves to provide feedback on the performance of the PM programme and offers a basis for programme modifications.

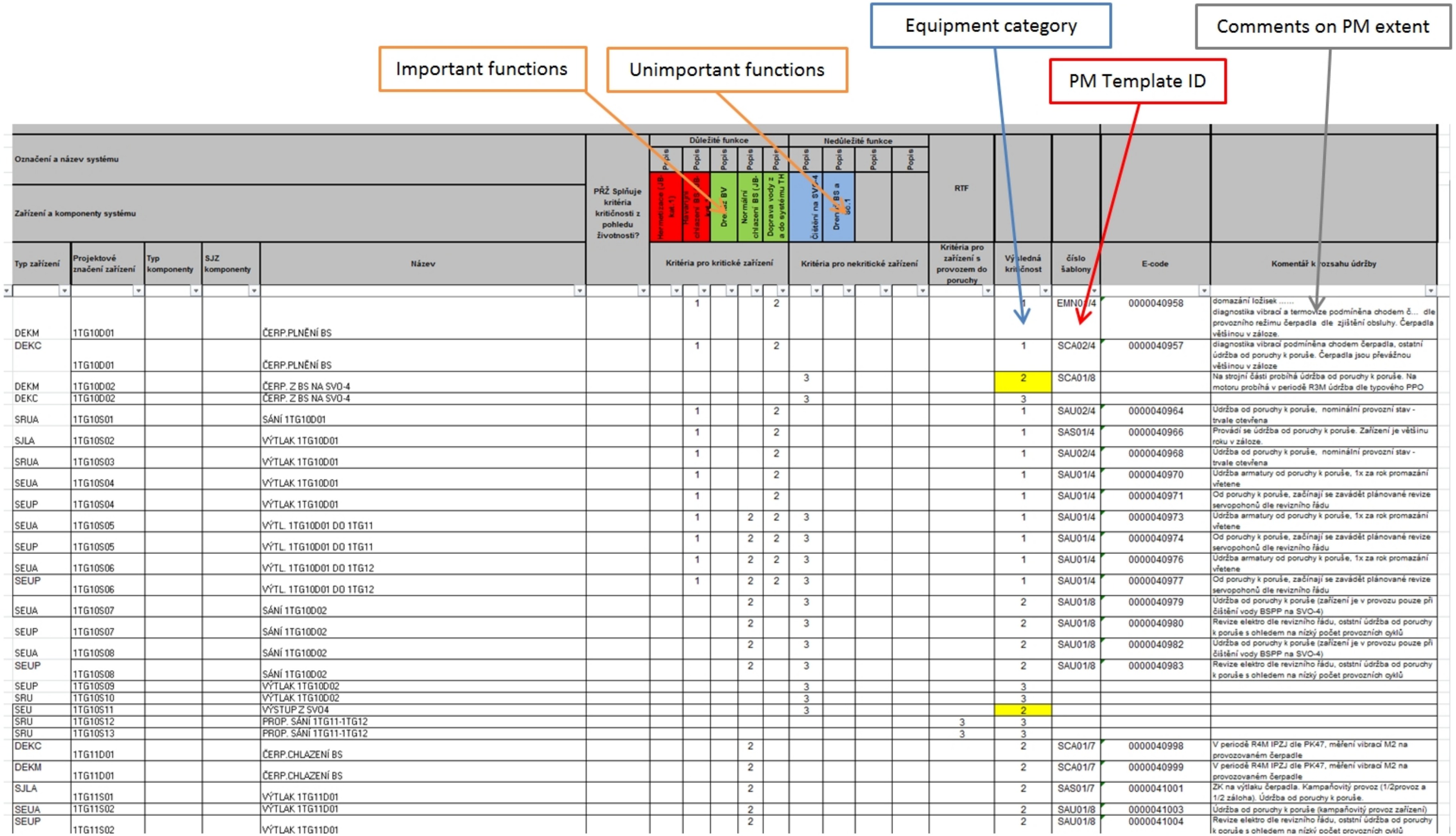
*IV-5.1.1. Evaluation areas*

- Safety and reliability;
- Shortcomings and operation events;
- Material condition;
- Influence on production losses;
- Technical modifications;
- Ageing management evaluation.

*IV-5.1.2. Evaluation output – health reports*

- Periodic report on TES condition;
- Elaborated once a year for each TES;
- Provides the basis for the operating licence renewal application.

# Criticality table (example)




Označení a název systému

Zařízení a komponenty systému

| Typ zařízení | Projektové značení zařízení | Typ komponenty | SJZ komponenty | Název | PŘŽ Splňuje kritéria kritičnosti z pohledu životnosti? | Důležité funkce – Popis: Hermetizace (JB-kat.1) | Důležité funkce – Popis: Havarijní chlazení BS (JB-kat.1) | Důležité funkce – Popis: Drenáž BV | Důležité funkce – Popis: Normální chlazení BS (JB-…) | Důležité funkce – Popis: Doprava vody z a do systému TH | Nedůležité funkce – Popis: Čištění na SVO-4 | Nedůležité funkce – Popis: Drenáž BS a …1 | Nedůležité funkce – Popis | Nedůležité funkce – Popis | RTF – Kritéria pro zařízení s provozem do poruchy | Výsledná kritičnost | číslo šablony | E-code | Komentář k rozsahu údržby |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Kritéria pro kritické zařízení | | | | | Kritéria pro nekritické zařízení | | | | | | | | |
| DEKM | 1TG10D01 | | | ČERP.PLNĚNÍ BS | | | 1 | | | 2 | | | | | | 1 | EMN01/4 | 0000040958 | domazání ložisek ...... diagnostika vibrací a termovize podmíněna chodem č... dle provozního režimu čerpadla dle zjištění obsluhy. Čerpadla většinou v záloze. |
| DEKC | 1TG10D01 | | | ČERP.PLNĚNÍ BS | | | 1 | | | 2 | | | | | | 1 | SCA02/4 | 0000040957 | diagnostika vibrací podmíněna chodem čerpadla, ostatní údržba od poruchy k poruše. Čerpadla jsou převážnou většinou v záloze |
| DEKM | 1TG10D02 | | | ČERP. Z BS NA SVO-4 | | | | | | | 3 | | | | | 2 | SCA01/8 | | Na strojní části probíhá údržba od poruchy k poruše. Na motoru probíhá v periodě R3M údržba dle typového PPO |
| DEKC | 1TG10D02 | | | ČERP. Z BS NA SVO-4 | | | | | | | 3 | | | | | 3 | | | |
| SRUA | 1TG10S01 | | | SÁNÍ 1TG10D01 | | | 1 | | | 2 | | | | | | 1 | SAU02/4 | 0000040964 | Údržba od poruchy k poruše, nominální provozní stav - trvale otevřena |
| SJLA | 1TG10S02 | | | VÝTLAK 1TG10D01 | | | 1 | | | 2 | | | | | | 1 | SAS01/4 | 0000040966 | Provádí se údržba od poruchy k poruše. Zařízení je většinu roku v záloze. |
| SRUA | 1TG10S03 | | | VÝTLAK 1TG10D01 | | | 1 | | | 2 | | | | | | 1 | SAU02/4 | 0000040968 | Údržba od poruchy k poruše, nominální provozní stav - trvale otevřena |
| SEUA | 1TG10S04 | | | VÝTLAK 1TG10D01 | | | 1 | | | 2 | | | | | | 1 | SAU01/4 | 0000040970 | Údržba armatury od poruchy k poruše, 1x za rok promazání vřetene |
| SEUP | 1TG10S04 | | | VÝTLAK 1TG10D01 | | | 1 | | | 2 | | | | | | 1 | SAU01/4 | 0000040971 | Od poruchy k poruše, začínají se zavádět plánované revize servopohonů dle revizního řádu |
| SEUA | 1TG10S05 | | | VÝTL. 1TG10D01 DO 1TG11 | | | 1 | | 2 | 2 | 3 | | | | | 1 | SAU01/4 | 0000040973 | Údržba armatury od poruchy k poruše, 1x za rok promazání vřetene |
| SEUP | 1TG10S05 | | | VÝTL. 1TG10D01 DO 1TG11 | | | 1 | | 2 | 2 | 3 | | | | | 1 | SAU01/4 | 0000040974 | Od poruchy k poruše, začínají se zavádět plánované revize servopohonů dle revizního řádu |
| SEUA | 1TG10S06 | | | VÝTL. 1TG10D01 DO 1TG12 | | | 1 | | 2 | 2 | 3 | | | | | 1 | SAU01/4 | 0000040976 | Údržba armatury od poruchy k poruše, 1x za rok promazání vřetene |
| SEUP | 1TG10S06 | | | VÝTL. 1TG10D01 DO 1TG12 | | | 1 | | 2 | 2 | 3 | | | | | 1 | SAU01/4 | 0000040977 | Od poruchy k poruše, začínají se zavádět plánované revize servopohonů dle revizního řádu |
| SEUA | 1TG10S07 | | | SÁNÍ 1TG10D02 | | | | | 2 | | 3 | | | | | 2 | SAU01/8 | 0000040979 | Údržba od poruchy k poruše (zařízení je v provozu pouze při čištění vody BSPP na SVO-4) |
| SEUP | 1TG10S07 | | | SÁNÍ 1TG10D02 | | | | | 2 | | 3 | | | | | 2 | SAU01/8 | 0000040980 | Revize elektro dle revizního řádu, ostatní údržba od poruchy k poruše s ohledem na nízký počet provozních cyklů |
| SEUA | 1TG10S08 | | | SÁNÍ 1TG10D02 | | | | | 2 | | 3 | | | | | 2 | SAU01/8 | 0000040982 | Údržba od poruchy k poruše (zařízení je v provozu pouze při čištění vody BSPP na SVO-4) |
| SEUP | 1TG10S08 | | | SÁNÍ 1TG10D02 | | | | | 2 | | 3 | | | | | 2 | SAU01/8 | 0000040983 | Revize elektro dle revizního řádu, ostatní údržba od poruchy k poruše s ohledem na nízký počet provozních cyklů |
| SEUP | 1TG10S09 | | | VÝTLAK 1TG10D02 | | | | | | | 3 | | | | | 3 | | | |
| SRU | 1TG10S10 | | | VÝTLAK 1TG10D02 | | | | | | | 3 | | | | | 3 | | | |
| SEU | 1TG10S11 | | | VÝSTUP Z SVO4 | | | | | | | 3 | | | | | 2 | | | |
| SRU | 1TG10S12 | | | PROP. SÁNÍ 1TG11-1TG12 | | | | | | | | | | | 3 | 3 | | | |
| SRU | 1TG10S13 | | | PROP. SÁNÍ 1TG11-1TG12 | | | | | | | | | | | 3 | 3 | | | |
| DEKC | 1TG11D01 | | | ČERP.CHLAZENÍ BS | | | | | 2 | | | | | | | 2 | SCA01/7 | 0000040998 | V periodě R4M IPZJ dle PK47, měření vibrací M2 na provozovaném čerpadle |
| DEKM | 1TG11D01 | | | ČERP.CHLAZENÍ BS | | | | | 2 | | | | | | | 2 | SCA01/7 | 0000040999 | V periodě R4M IPZJ dle PK47, měření vibrací M2 na provozovaném čerpadle |
| SJLA | 1TG11S01 | | | VÝTLAK 1TG11D01 | | | | | 2 | | | | | | | 2 | SAS01/7 | 0000041001 | ZK na výtlaku čerpadla. Kampaňovitý provoz (1/2provoz a 1/2 záloha). Údržba od poruchy k poruše. |
| SEUA | 1TG11S02 | | | VÝTLAK 1TG11D01 | | | | | 2 | | | | | | | 2 | SAU01/8 | 0000041003 | Údržba od poruchy k poruše (kampaňovitý provoz zařízení) |
| SEUP | 1TG11S02 | | | VÝTLAK 1TG11D01 | | | | | 2 | | | | | | | 2 | SAU01/8 | 0000041004 | Revize elektro dle revizního řádu, ostatní údržba od poruchy k poruše s ohledem na nízký počet provozních cyklů |

*FIG. IV-3. Criticality table.*

ANNEX V.
# INSIGHTS OF PREDICTIVE MAINTENANCE IMPLEMENTATION IN NUCLEAR POWER PLANTS

## *KHNP Case Study*

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Korea Hydro & Nuclear Power Co., LTD,
REPUBLIC OF KOREA

**Summary**

Most utilities are endeavouring to improve plant performance by preventing equipment failures which could lead to plant shutdown or power loss. Maintenance strategies are changed from corrective maintenance to preventive maintenance to minimize resources and cost of maintenance. To identify the condition of component degradation, several predictive maintenances have been introduced and implemented. Moreover, as on–line condition monitoring technologies are rapidly developed, early warning and prognostic maintenance are introduced to identify any adverse trends in advance.
Korea Hydro & Nuclear Power Company (KHNP) has been developing a PM template for all component types used at operating units and is currently optimizing the preventive maintenance of all operating units. Five CM technologies have been implemented as predictive maintenance; some of the cases identified through these will be addressed. KHNP is also developing a centralized on–line monitoring and prognostic analysis system to identify adverse trends with early warning technology which compares relative parameters with that of conditions derived from previous experienced patterns of abnormal conditions.
Keywords – Predictive Maintenance, Condition Based Maintenance, On–line Monitoring.

## V-1. INTRODUCTION

Most utilities are endeavouring to prevent equipment failure which could lead to plant shutdown or power de–rating of a plant. Many methodologies and maintenance strategies have been developed and introduced to meet this purpose. At the first stage of introduction of preventive maintenance, most believe that equipment failure dominantly relies on operating age. To minimize equipment failure and degradation caused by ageing, scheduled maintenance including periodic inspection, test and maintenance, have been performed. However, not all components are failed or degraded by ageing degradation. It is not just one or two, but six failure patterns that occur in practice and the study of civil aircrafts shows the composition of the failure mechanism as depicted in FIG. V-1, which shows quite different results from a traditional maintenance strategy based on the failure mechanism [V-1].

In some cases, excessive scheduled maintenance may lead to an increase in overall failure rates due to human intervention and infant mortality to the stable systems. Many tasks as PM have been completed, but many more maintenance tasks that are essential to the safe operation of modern, complex industrial systems do not appear in the associated maintenance programmes, in alignment with the saying, “doing the right job is more important than doing the job right.” Monitoring of the components is gradually increased to identify degradation before failure. By the aid of the technologies, components of CM technologies are rapidly developed and introduced. Most utilities are attempting to implement and increase condition based maintenance.

| Failure mode | Ratio(%) | Componenttype | PM Strategy |
|---|---|---|---|
| failure / Wear Out / time | 2% | Bearing | Periodic Maintenance + Condition Monitoring |
| failure / Bathtub / time | 4% | General | Periodic Maintenance + Performance Test |
| failure / Increasing / time | 5% | Pipe coating | Periodic Maintenance |
| failure / Wear In / time | 7% | Compressor | Periodic Maintenance + Condition Monitoring |
| failure / Random Failure / time | 14% | Lubricant | Periodic Maintenance + Condition Monitoring |
| failure / Infant+Random failure / time | 68% | Electronic Card | Periodic Maintenance + Condition Monitoring + Pre-installation test |

*FIG. V-1. Failure pattern and composition of failure from the study.*

Korea Hydro and Nuclear Power Company developed PM templates for 201 component types based on the failure mechanism referring to EPRI PMBD – example is on FIG. V-2. The PM templates are implemented to optimize the current PM according to functional importance, environmental conditions and duty cycles of components. These are in progress with the standardization of the task list and resources for each type of component.

| Rev | 2 | PM Template | | | | | | Class1 | Pump |
|---|---|---|---|---|---|---|---|---|---|
| Date | '10.11.05 | | | | | | | Class2 | PPHC |
| FID(Functional Importance) | | | | | | | | | Horizontal Pump |
| Importance | Critical | | | | Minor | | | | |
| Op. Frequency | High | Low | High | Low | High | Low | High | Low | |
| Op. Environment | Severe | | Mild | | Severe | | Mild | | |
| PM Task | CHS | CLS | CHM | CLM | MHS | MLS | MHM | MLM | |
| Condition Monitoring Task | Frequency | | | | | | | | Reference |
| Vibration Analysis | 1M | 1M | 1M | 1M | 3M | 3M | 3M | 3M | EPRI, Industry Template |
| Lubricant Analysis | 3M | 1F | 3M | 1F | 1F | 1F | 1F | AR | EPRI, Industry Template |
| Performance Monitoring | 6M | 6M | 6M | 6M | 6M | 6M | 1F | 1F | EPRI, Industry Template |
| IR(Infra-Red) Analysis | 6M | 6M | 6M | 6M | 12M | 12M | 12M | 12M | EPRI, OE |
| Operator Shift Log | 1S | 1S | 1S | 1S | 1D | 1D | 1D | 1D | EPRI |
| Time Directed Task | Frequency | | | | | | | | Reference |
| Coupling check | 2F | 3F | 2F | 3F | AR | AR | AR | AR | OE, Industry Template |
| Nozzle NDT | 6F | AR | 6F | AR | 6F | AR | 6F | AR | OE, Industry Template |
| Partial overhaul | AR | AR | AR | AR | AR | AR | AR | AR | EPRI, Industry Template |
| Failure Finding Task | | | | | | | | | |
| Functional Test | AR | AR | AR | AR | AR | AR | AR | AR | EPRI, Industry Template |

*FIG. V-2. Example of KHNP's PM template for horizontal pump (PPHC) type.*

KHNP also introduced five CM technologies as predictive maintenance: vibration analysis; infrared thermography; oil analysis; airborne ultrasonic analysis; and motor current analysis.

These technologies help to identify the conditions of equipment and to decide maintenance planning and scheduling of components from the results of analysis. To obtain the appropriate information, data collection, performance of detection tools and analysis programme are very important, however, skills and experience of analysis are much more crucial for the success of predictive maintenance. An early warning system is also being developed to give notification when some parameters of a component reach over a set point or a similar pattern of previous failure occurs. The set point is preliminary determined to be lower than the alarm set point.

This paper presents the implementation of predictive maintenance in KHNP as well as a general introduction of predictive maintenance. The effectiveness and future plan of PdM will also be discussed.

## V-2. PREDICTIVE MAINTENANCE USED IN NUCLEAR POWER PLANTS

KHNP's predictive maintenance system consists of an on–line diagnostic system and an off-line diagnostic system. The on–line diagnostic system utilizes vibration signals and temperature sensors of large rotating equipment such as the turbine–generator, reactor coolant pumps, feedwater pumps, etc. The on–line signals are monitored in the main control room (MCR) and by the plant information system. When each parameter exceeds a pre–designated alarm threshold, a warning signal is triggered.

KHNP's off-line PdM system, the Machinery Health Management (MHM) system, is utilized for medium and small sized rotating equipment and other types of equipment in which on–line instrument sensors are not installed (FIG. V-3). Hand–held instruments are used to measure vibration signals and ultrasonic signals as well as to take infrared images. Lube oil samples are collected manually and analysed by the oil analysis machine. The collected data is transferred to the plant PdM server directly or through local terminals to analyse the conditions of measured components and to save the data for trending. Work orders for data collection, sampling or analysis are issued automatically in a timely manner with designated maintenance tasks and frequency through work management modules of the Enterprise Resource Planning (ERP) system. The module also generates a work order manually when CM is required.

Predictive maintenance work activities are divided by data collecting works and analysis works which evaluate equipment status. Both works are required to be done by qualified workers of appropriate levels. Data collection requires internal qualification which is given by training and practicing of works under supervision of qualified staff. Predictive maintenance analysis work requires an advanced level of qualification or certification from an external organization which holds an international certification programme such as ISO 18436 "Condition Monitoring and Diagnostics of Machines – Requirements for Qualification and Assessment of Personnel." Each technology requires its own certifications and qualifications, so the requirement for the worker and the analyst should be described in the CM Procedure. The quality of PdM works depends on the technical level of workers and analysts. Continuous training and qualification management are critical to identify the problem and the quality of predictive maintenance.

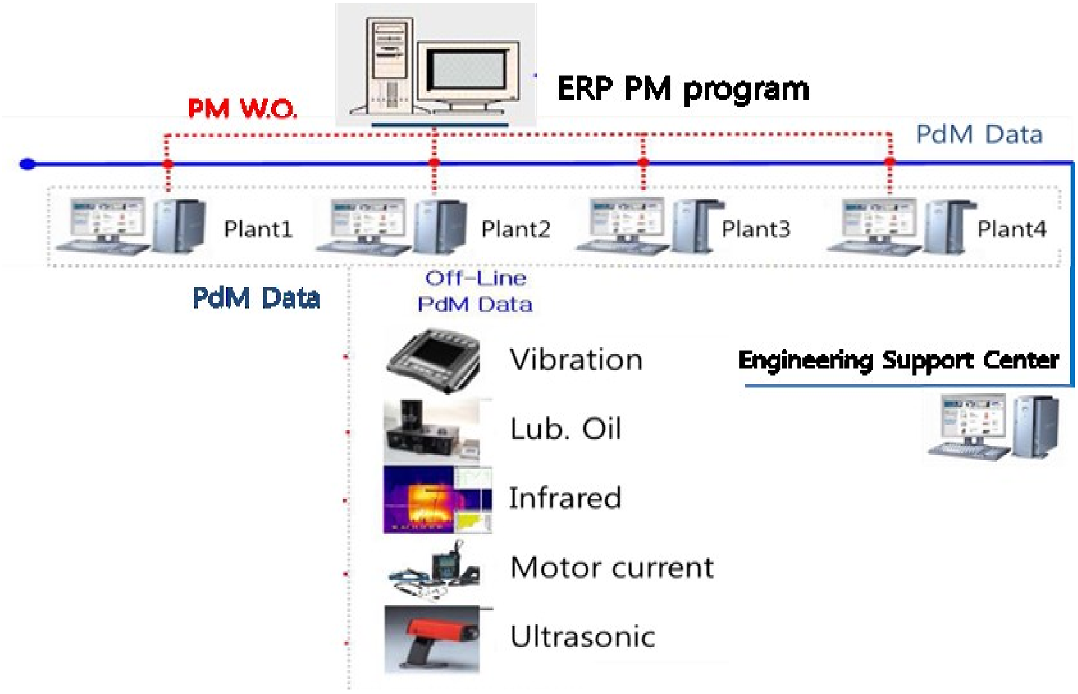



*FIG. V-3. Schematic diagram of KHNP's predictive maintenance system (MHM).*

Vibration analysis is a major activity for predictive maintenance, accounting for about 56% of all CM activities while thermography accounts for 35% and lube–oil analysis accounts for 9% as depicted in FIG. V-4. Vibration analysis is the most effective tool for degradation monitoring of rotating equipment and some large components such as transformers. The vibration monitoring activities of equipment are shown in FIG. V-5.

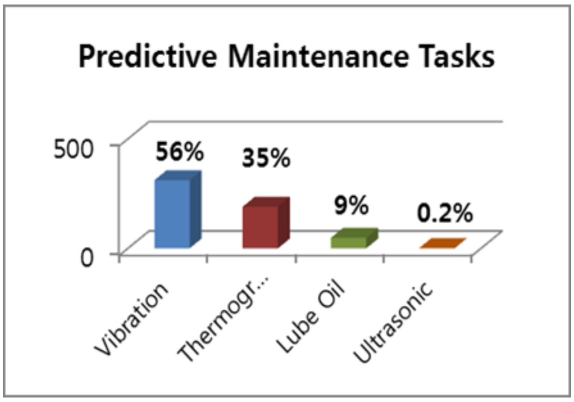



*FIG. V-4. Condition monitoring status.*

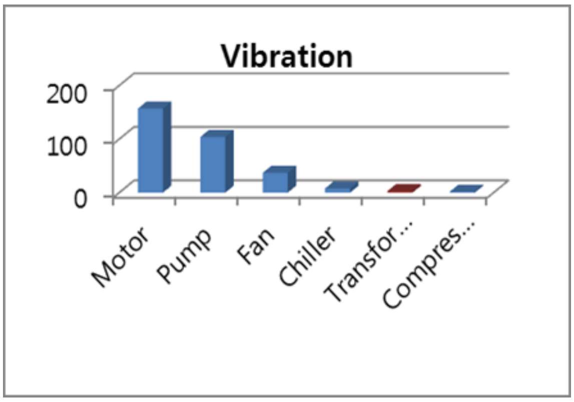



*FIG. V-5. Equipment of vibration monitoring.*

Infrared thermography is applicable to monitor the condition of electric equipment and instruments, and is also applicable to leakage monitoring of the steam trap. Oil analysis monitors the viscosity, ferrography and particle count of lube oil samples of rotating equipment. Because the oil analyser requires a large quantity of oil samples, this technology has been only applicable to the equipment which has more than 10 gallons of oil reserves to prevent interrupting the lube oil system of the equipment. KHNP is planning to replace the oil analyser with a new analyser which requires a smaller quantity of oil samples. Ultrasonic analysis is applicable to the steam trap and transformers. The infrared thermography and ultrasonic analysis activities of equipment are shown in FIG. V-6 and FIG. V-7.

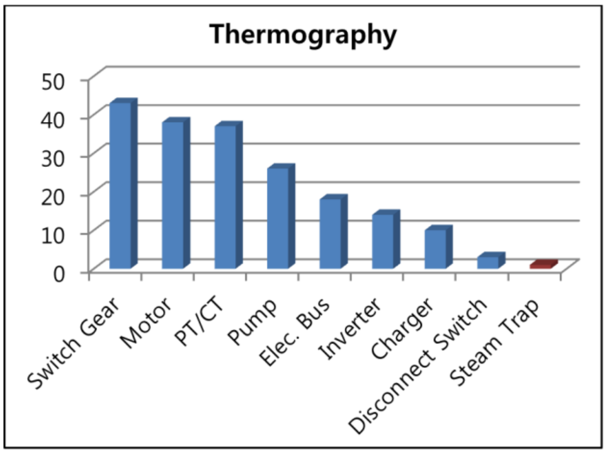



*FIG. V-6. Equipment of Thermography.*

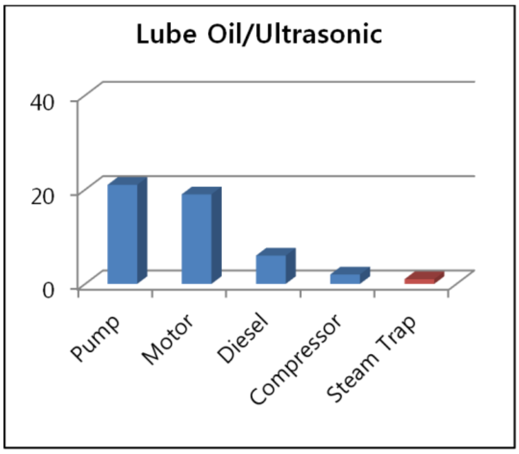



*FIG. V-7. Equipment of Lube Oil/Ultrasonic.*

Motor current analysis is applicable to the high voltage squirrel cage induction motor. It is temporarily suspended until a safer way is introduced, because it is considered possible to make a short circuit or be hazardous to the workers when measuring the current.

Predictive maintenance evaluation results are classified into four grades, which are red, yellow, white and green – see Table V-1. When the result of CM is yellow or red, the PdM coordinator issues a notification through a CAP and informs the component engineer in charge. Then, the PdM technical area owner identifies the possible causes and prepares a component status report.

Table V–1. PREDICTIVE MAINTENANCE EVALUATION GRADE AND STATUS

| Grade | Red (Action) | Yellow (Warning) | White (Monitoring) | Green (Good) |
|---|---|---|---|---|
| Status | Exceeds tolerance limit | Exceeds normal operating range or abnormal trends | Within the limit, but degrading trends | Good condition |

A component engineer is assigned as an owner of cause evaluation when a notification is issued through the CAP process. When the issued notification is a significant level 1 or 2, RCA or ACE should be performed with an appropriate corrective action including a recovery action plan or maintenance. One of the corrective actions is to change the PM frequency if required.

## V-3. SEVERAL EXAMPLES OF CONDITION MONITORING ACTIVITIES

### V-3.1. Thermography

Thermography utilizes infrared images of heating equipment. As depicted in FIG. V-8, the thermography images show the temperature difference on the main transformer phase ‘C’ control panel. Contact between wire #A and MCCB #1 (left side of the image) is loosened to increase temperature, comparing to MCCB #2 (right side of the image). This was cleared by tightening the wire. The temperature of ‘C’ phase of Non–Segregated Phase Bus (NSPB) of Non–1E 13.8KV circuit breaker is higher than the other breaker connection as shown in FIG. V-9 due to poor connection of the circuit breaker.

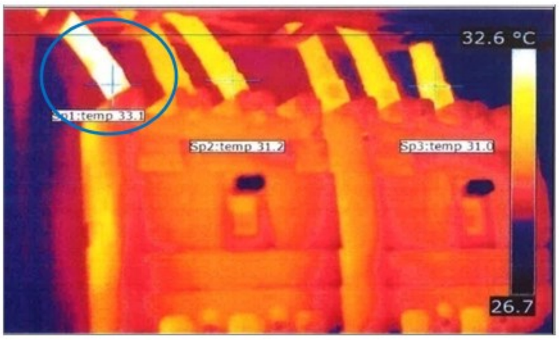



*FIG. V-8. Main Transformer Phase C Control Panel.*

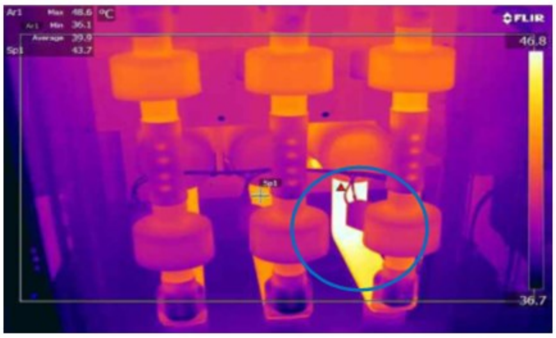



*FIG. V-9. NSPB of Non–1E 13.8KV CB.*

FIG. V-10 shows the motor side temperature of the condenser hot–well sampling pump which has been increased by 59℃ from the normal temperature of 32℃ because of the damaged cooling fan. The temperature differs on the connection bolt of the ground wire at the Main Transformer phase ‘A’ Gas Isolated Bus (GIB) as shown in FIG. V-11, because the leakage current from a circulating current induced increased temperature. Grinding the connection point and bolt tightening work were performed for recovery.

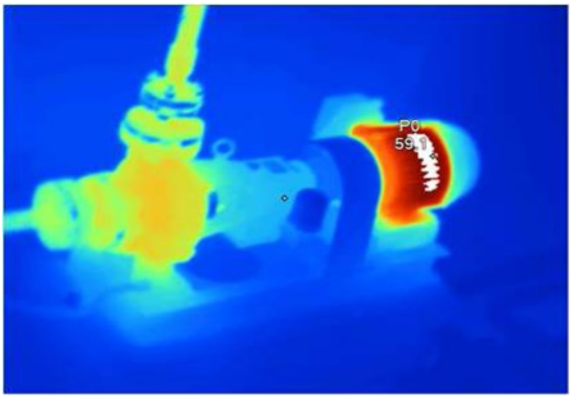


*FIG. V-10. Condenser Hotwell Sampling Pump.*

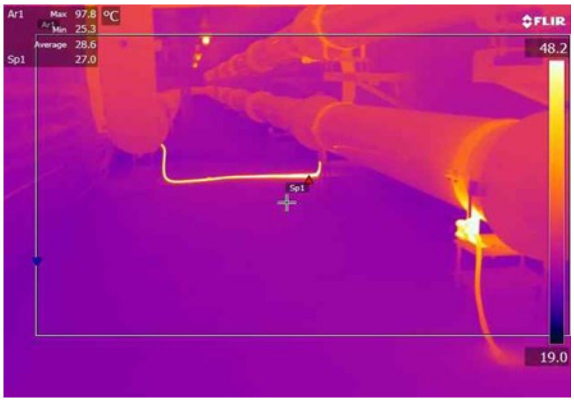



*FIG. V-11. Main Transformer A GIB Ground Wire.*

### V-3.2. Lube oil analysis

Lube oil analysis is one of the most effective tools with vibration analysis to find the degradation of rotating equipment. FIG. V-12 shows that the lube oil sample of circulating water pump motor upper bearing has been discoloured. The particle count on the sleeve/rolling bearing was approximately 77,800 (ISO grade 23) for >4$\mu$mparticle and 22,000 (ISO grade 22), where the management levels are grade 21 (count 10,000~ 20,000) for > 4$\mu$m and grade 19 (count 2,500~5,000) for > 6$\mu$m. Bearing wear with muddy water during the winter season is a possible reason for this and the contaminated lube oil was replaced. Table V–2 shows the results of the lube oil analysis on the main feedwater pump. The water content level (management level 0.1%) was increased to 1.38%. Further investigation found that seal water was entered into the lube oil.


*FIG. V-12. Circulating water pump motor upper bearing.*

Table V–2. LUBE OIL ANALYSIS RESULTS OF MAIN FEEDWATER PUMP (541–M–PP01)

| Ref Oil | No Reference Oil | | | | |
|---|---|---|---|---|---|
| Sample Date | 2013–09–05 | 2013–08–23 | 2013–08–22 | 2013–08–21 | 2013–08–21 |
| Sample # | 289210 | 285522 | 283404 | 283401 | 283398 |
| Unit Usage – hrs | | | | | |
| Oil Usage – hrs | | | | | |
| Oil Added – aus | | | | | |
| Contamination | 0 | 0 | 0 | 83 | 74 |
| Contam Idx – Idx | 0.0 | 1.6 | 19.6 | 436.9 | 195.7 |
| % Water – % | 0.0001 | 0.0051 | 0.0621 | 1.3816 | 0.6187 |

Ferrography analysis on the circulating water pump is shown in FIG. V-13. The Ferro Index was measured by 1.4 and several particles of metallic debris were found in the Wear Debris Analysis (WDA) using an electron microscope.

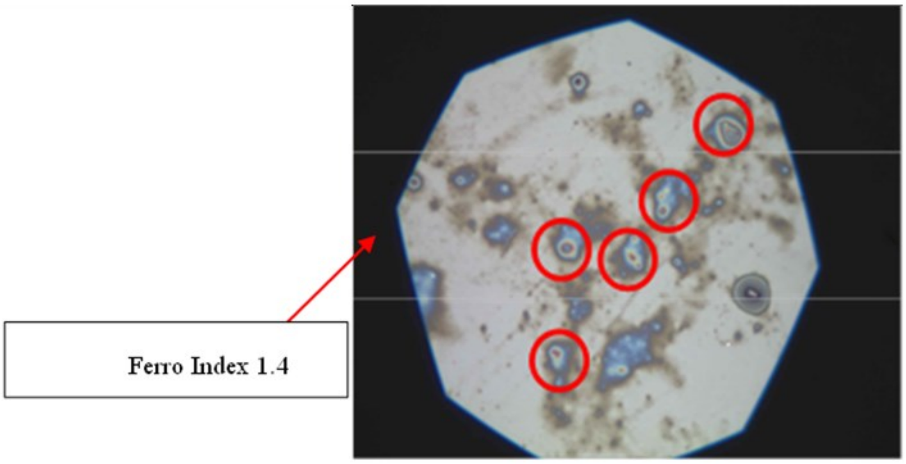



*FIG. V-13. CW Pump (551–M–PP03) Lube Oil Analysis and Electron Microscope Analysis.*

### V-3.3. Ultrasonic analysis

An example of ultrasonic analysis is shown in FIG. V-14 as ultrasonic analysis on the Aux Steam Header Steam Trap by an ultrasonic instrument. This measures the difference between the maximum and minimum sound levels when the trap is actuated. Internal leakage was found at the trap when it dismantled and the trap was replaced with a new one.

*FIG. V-14. Steam Trap (FA–ST006) Ultrasonic Analysis.*

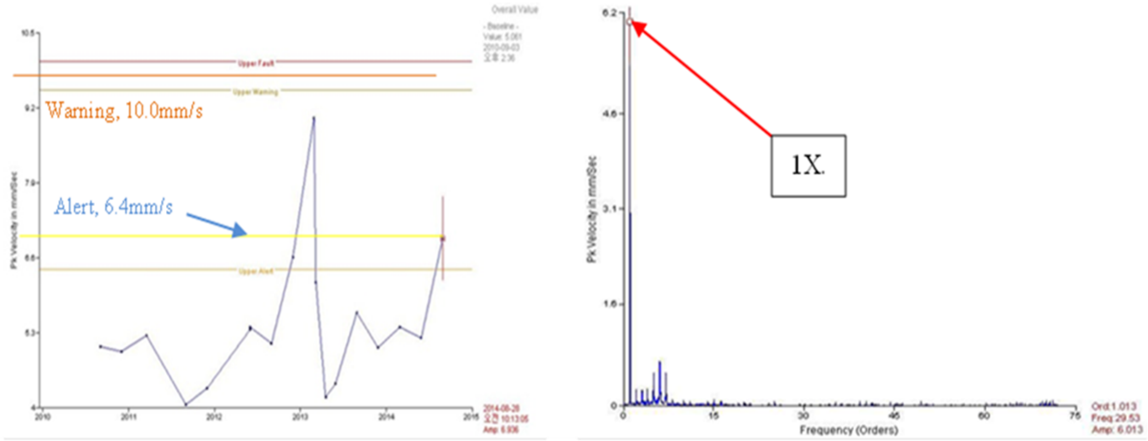
### V-3.4. Vibration analysis

During vibration measurement on the spent fuel bay transfer pump by a handheld vibration instrument, the pump inboard horizontal (PIH) vibration level was 9.2 mm/s which exceeded the alert level of 8.3 mm/s as depicted in FIG. V-15. Further investigation found that the bearing supporter was an abnormal vibration source, and the weak vibration supporter was replaced.

| | PIH | PIV | POH |
|---|---|---|---|
| Alert (mm/s) | 8.3 | 4.5 | 4.5 |
| Dec. 10 | 6.5 | 2.4 | 1.4 |
| Jan. 2 | 7.7 | 2.6 | 1.5 |
| Mar. 22 | 9.2 | 3.2 | 1.6 |

*FIG. V-15. Spent Fuel Bay Transfer Pump Vibration Analysis.*

FIG. V-16 shows that the pump rotation frequency (1x) exceeds the alert level of 6.4mm/s in the vibration analysis on the sluice water pump. It was found that the loosened impeller fastening nut was the source.




| | MIV | MIH | PIV | PIH |
|---|---|---|---|---|
| Alert (mm/s) | 6.4 | | | |
| Aug. 28 | 1.37 | 0.81 | 2.25 | 6.94 |

*FIG. V-16. Sluice Water Pump Vibration Analysis.*

### V-3.5. Predictive maintenance programme assessment report

The plant PdM programme owner evaluates the PdM programme activities every quarter for each of the CM activities including the number of components, and prepares PdM status reports if the condition monitoring is in red or yellow. When the condition is white, the PdM status report is optional. The assessment report also shows the evaluation trend to compare with the evaluation results of the previous three quarters – see FIG. V-17.

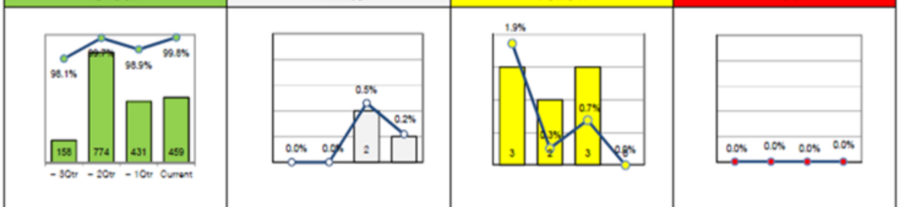
**2014 3rd Qtr PdM Program Assessment Report**

**Ⅰ. PdM Program Performance**

○ PdM work result

| Technical area | Plan | Actual | Additional | Evaluation Result | | | | PdM Status Report |
|---|---|---|---|---|---|---|---|---|
| | | | | Green | White | Yellow | Red | |
| Vibration | 482 | 220 | 34 | 219 | 1 | 0 | 0 | 2 |
| Lube Oil | 24 | 24 | 0 | 24 | 0 | 0 | 0 | 0 |
| Thermography | 298 | 216 | 0 | 216 | 0 | 0 | 0 | 0 |
| Ultrasonic | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Total | 804 | 460 | 34 | 459 | 1 | 0 | 0 | 2 |

○ PdM evaluation trend



| Green | | | | White | | | | Yellow | | | | Red | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| - 3Qtr | - 2Qtr | - 1Qtr | Current | - 3Qtr | - 4Qtr | - 1Qtr | Current | - 3Qtr | - 4Qtr | - 1Qtr | Current | - 3Qtr | - 4Qtr | - 1Qtr | Current |
| 98.1% | 99.7% | 98.9% | 99.8% | 0.0% | 0.0% | 0.5% | 0.2% | 1.9% | 0.3% | 0.7% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% |
| 158 | 774 | 431 | 459 | 0 | 0 | 2 | 1 | 3 | 2 | 3 | 0 | 0 | 0 | 0 | 0 |

*FIG. V-17. Example of a quarterly PdM programme assessment report.*

The corporate PdM programme owner evaluates the fleet–wide PdM programme status by periodically reviewing the plant PdM programme assessment reports. The evaluation results are notified to the plant PdM owners at the PdM working group meeting to discuss opportunities for improvement. KHNP's fleet–wide PdM programme assessment results in 2013 show that the red/yellow grade is less than 0.3% and that the white grade is 0.6% while 99% of components are evaluated as a green grade as shown in FIG. V-18.

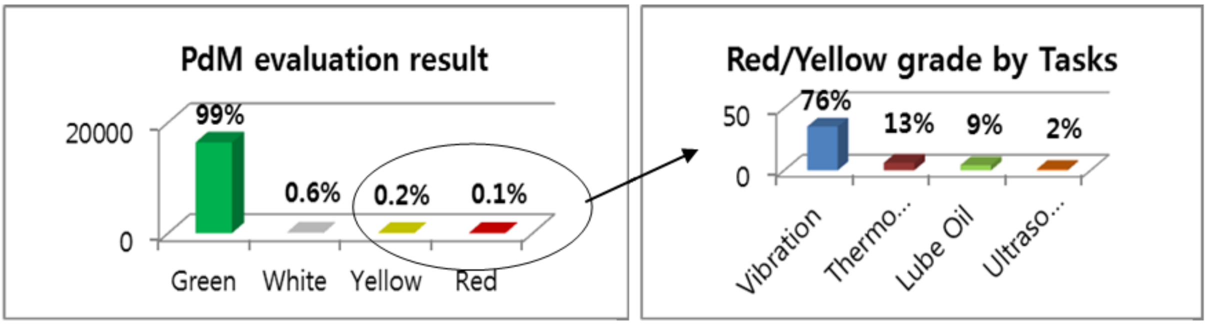



*FIG. V-18. Annual PdM evaluation results.*

Condition based maintenance is a process that requires technologies and people skills, and combines and uses all available direct diagnostic and performance data, process parameter trends, operator logs, and visual inspections to make and communicate timely recommendations regarding corrective actions or maintenance requirements of major/critical equipment. From the EPRI TR–1022957, the industry obtained the following benefits by implementing condition based maintenance [V-2]:

- Allowing for costly and intrusive time based maintenance activities to be extended in frequency or eliminated by using CM technologies to identify failures at early stages of degradation;
- Quantitatively avoided cost savings and reduction of equipment out–of–service times by detecting equipment anomalies at early stages;
- Qualitative benefits including reduced infant mortality via elimination of intrusive time based tasks, assisting with troubleshooting, enhanced post–maintenance testing;
- Maintaining/improving equipment reliability in today's environment, where manpower and funding have been, and continue to be, reduced.

## V-4. ON–LINE MONITORING AND EARLY WARNING SYSTEM

Process parameter trending is one of the CM technologies and system/component health monitoring activities. On–line monitoring technology uses on–line signals to monitor equipment performance and offers an alternative method to traditional time–directed PM.

Traditional approaches to condition assessment require equipment experts to survey a number of plant parameters, trend them individually, conduct visual examinations and review supervisory instrumentation to determine equipment health. The limitations of traditional approaches are derived mainly from their inability to look simultaneously at all parameters that either influence, or are influenced by, a particular component degradation. These limitations mean that interactions among various components of a system or between systems can be difficult to identify. This technique applies filters and compares the data values to limit more restrictively. Moving beyond techniques of simple trending leads to approaches based on empirical, data–driven modelling, including Advanced Pattern Recognition (APR) modelling. These tools have the capability of automatically analysing trends between multiple variables and indicating when the current trends deviate from the normal trends, based on historical operating data.

Empirical based modelling is to define how a given component operates in a normal state and develop a model that determines the relative value of each given point as compared to all points in the data set. Once a model is developed, the model can evaluate subsequent data to detect whenever the relative value of a point has changed. Changes detected with this approach are commonly referred to as anomalies [V-3].

Several empirical modelling technologies have been used for pattern recognition and data processing technologies for early warning system. The Auto Associative Kernel Regression (AAKR), Auto Associative Neural Network (AANN) and Multivariate State Estimation Technique (MSET) are widely used for this purpose [V-4].

The MSET which is a proprietary technique developed at Argonne National Laboratory and used in SmartSignal Inc.'s eCMTM system, the AANN used in Halden Reactor Project's PEANO system, AAKR, a non–proprietary technique which is very similar to MSET [V-5].

AAKR is a non–parametric, empirical modelling technique that uses historical, fault–free observations to correct any errors present in current observations.

The MSET can be used to monitor multiple parameters of the product, such as the temperature, humidity and vibration; and calculate the residuals between the actual and expected values of these parameters based on the healthy historic data. The MSET can detect the incipient of the fault of a product by comparing the residuals with the threshold and provide the necessary information required to make a remaining useful life prediction [V-6].

From the early 2000s, U.S. utilities adopted a centralized on–line monitoring centre for fossil plants, which were subsequently expanded to nuclear power plants based on the success in early detection of equipment anomalies avoiding catastrophic failure. When first introducing the on–line monitoring centre, staff spent a large portion of their time maintaining the APR model. The utilities were able to reduce spending time for model management since most APR models have been created tuned. Some utilities have a centralized on–line monitoring centre and other utilities have distributed its function to the power plants which have a system engineering organization to monitor systems and equipment.

KHNP introduced the on–line monitoring centre in 2015 (FIG. V-19). The KHNP on–line monitoring centre adopts already proven commercial APR software. To enhance the monitoring capability, additional data acquisition servers are installed at the plants. The server collects the data from the plant monitoring system every second and sends the data to the on–line monitoring centre. The plant on–line vibration signals and other available data sources are connected to the on–line monitoring system.

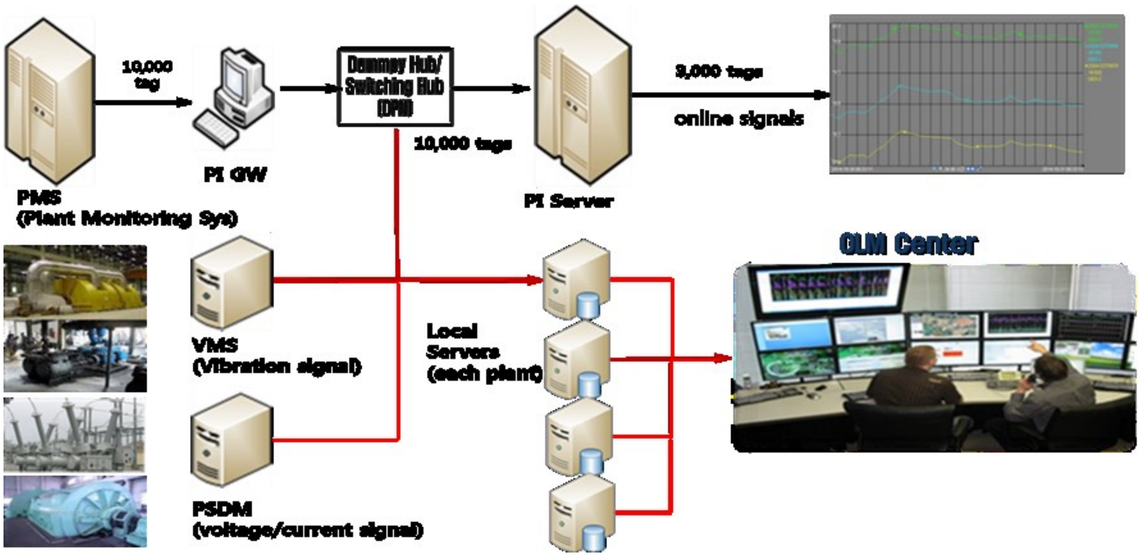



*FIG. V-19. Schematic diagram of KHNP's on–line monitoring centre.*

## V-5. CONCLUSIONS

KHNP is making efforts to improve equipment reliability by means of PM before equipment failure. Standardization of PM tasks and frequencies are based on equipment type and manufacturer by using a PM template which determines those according to component classification, environmental conditions and duty cycles.

To detect degradation of components, KHNP has implemented five PdM methodologies. Through these, several degradations or adverse trending has been found so that the equipment is fixed or recovered in advance to prevent failure with reasonable resources and time. These are also helpful for analysis and trending when the equipment has trouble. Vibration analysis is mainly used because it is widely implemented in the industry and there are many experts that can perform the analysis. To identify equipment degradation which cannot be found with vibration analysis, other methodologies such as infrared thermography, lube oil analysis and ultrasonic analysis should be used.

The most important factor for the successful implementation of PdM is data collection and analysis. For these, state–of–the–art devices, data collection points and expertise of engineers are essential.

Recently, monitoring technologies have been greatly improved and widely developed. Early warning and prognostic maintenance with on–line monitoring will be improved with equipment reliability to identify the conditions of equipment and to realize the remaining lifetime in advance. Centralized monitoring using these technologies will be more useful for the utilities that have many units at different sites.

## REFERENCES TO ANNEX V


[V-1] MOUBRY, J., Reliability Centred Maintenance, 2nd ed, Industrial Press (2001) pp 12–14.

[V-2] ELECTRIC POWER RESEARCH INSTITUTE, Condition Based Maintenance Guideline EPRI TR–1022957 (2011) p 2–1.

[V-3] ELECTRIC POWER RESEARCH INSTITUTE, Guideline for On–line Monitoring of Nuclear Power Plants, EPRI TR–1023031 Vol. 2 (2011).

[V-4] KIM, D. W., KIM, Y. S., KIM, H. G., LEE, B. O., A Status of Development of On–line Monitoring and Diagnostic Technique for Main Equipment in Nuclear Power Plant, KPVP (2014).

[V-5] HINES, J. W., GARVEY, D. R., Development and Application of Fault Detectability Performance Metrics for Instrument Calibration Verification and Anomaly Detection, Journal of Pattern Recognition Research 1 (2006) pp 2–15.

[V-6] CHENG, S., PECHT, M., Multivariate State Estimation Technique for Remaining Useful Life, Association for the Advancement of Artificial Intelligence (2007), www.aaai.org

# ANNEX VI.
# IMPROVING EQUIPMENT RELIABILITY WITH FEWER RESOURCES THROUGH INNOVATIVE CONDITION BASED MONITORING TECHNOLOGY

***Exelon Case Study***

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Byron Nuclear Power Plant
EXELON Corporation
UNITED STATES OF AMERICA

**Summary**

Exelon's Byron Station has consistently been one of Exelon's top performing nuclear power stations. Even with top quartile performance, Byron Station is challenged economically due to the sites location on the grid and the proximity to large scale subsidized renewable generation facilities especially wind and low cost natural gas generation. Exelon has pressed this challenge head–on through many fronts including innovative condition based monitoring programme.

## VI-1. INTRODUCTION

Byron Station, a top quartile performing plant is challenged economically due to large scale subsidized renewable generation facilities and low cost natural gas generation all competing for the same local market and access to a constrained transmission grid. Exelon has pressed this challenge head–on through many fronts including the use of technology to optimize resources while at the same time to improve equipment reliability. Byron Station has a long history of being the lead–plant that demonstrates a technology's potential benefit. For the advancement in condition based monitoring, Byron Station once again took the lead.

The purpose for condition based monitoring:

- Build advance monitoring infrastructure capable of significant advancements in system monitoring, diagnostics and prognostics capabilities;
- Leverage technology for system and component monitoring and obtain critical plant data in OSIsoft PI data historian;
- Improve plant reliability and maximize availability of safety systems in operator hands;
- Utilize critical plant resources for data analysis and diagnostics rather than data collection;
- Utilize wireless infrastructure to enhance equipment monitoring and switch limited time based preventive maintenance to condition based preventive maintenance;
- Optimize Byron PM strategy;
- Operate nuclear plants sustainably protecting public safety and gain public trust.

The drivers for implementing CBM at Byron Station are:

- Engineering lacks monitoring capabilities, which hinder their ability to diagnose plant issues efficiently. Advanced technology also helps with knowledge transfer and retention;

- Operation has problems in areas with no instrumentation and instrumentation located in high dose areas. In addition, critical operations resources are spent in data collection rather than responding to plant problems;
- For the maintenance department, PM specialists spends over 50% of their time in data collection instead of data analysis. Resources are committed to PM tasks (time based) that are not needed. Incomplete diagnostics due to lack of data or data at discrete sources.

The history of this evolution can be seen in FIG. VI-1 below.

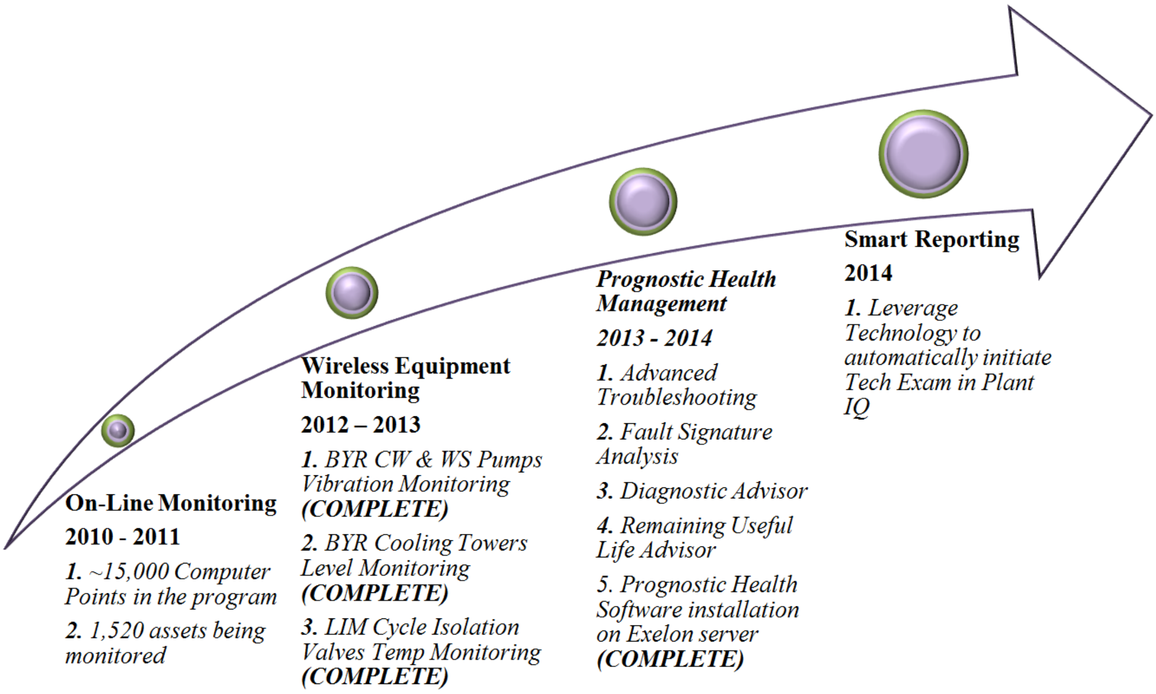


*FIG. VI-1. History of Byron Stations advanced monitoring infrastructure.*

## VI-2. ON–LINE MONITORING

The on–line monitoring program is a pattern recognition application that monitors plant parameters in real time. The program acquires raw data from plant data historian and is designed to provide early identification of degrading trends by continuously comparing real time plant data with historical good data.

Plant staff is automatically notified by email or pager when the OLM program identifies deviation. The program is currently used by engineering, maintenance and operations. After successful deployment there are approximately 15,000 computer points monitored over 1,450 assets across Exelon’s fleet. The information technology (IT) architecture summary for OLM is shown in FIG. VI-2 below.

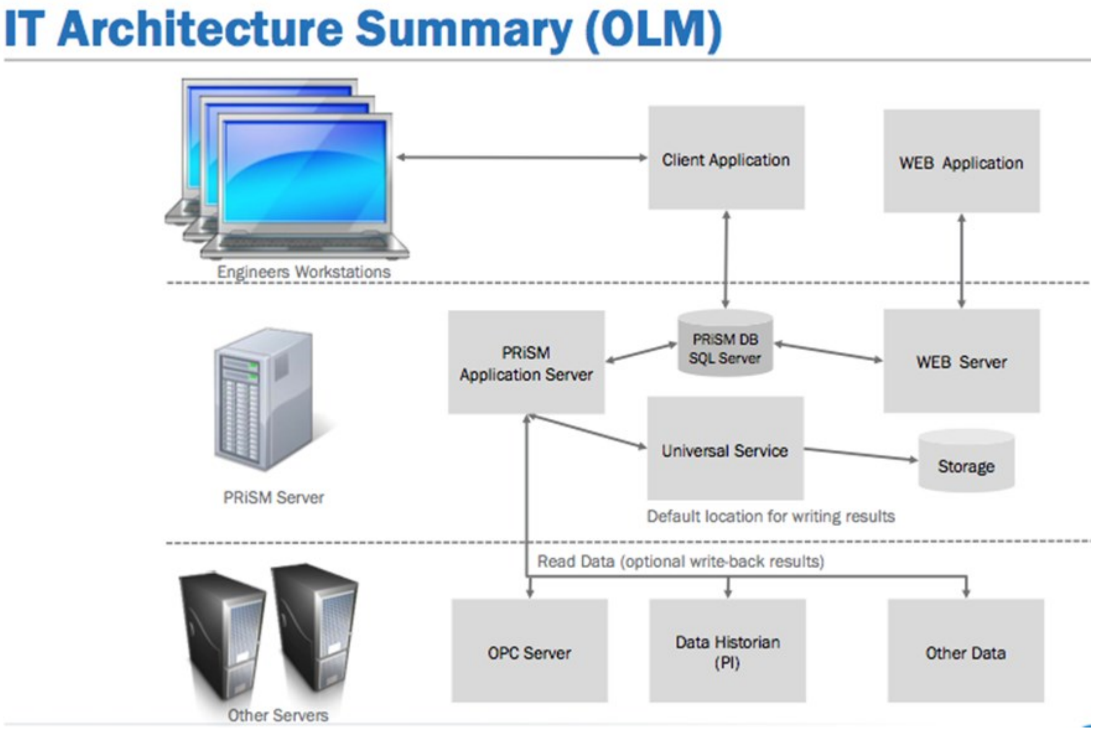


*FIG. VI-2. IT Architecture summary on–line monitoring.*

On–line monitoring has had a number of catches that have prevented unit de–rates, unit trips and avoided significant equipment damage, shown in FIG. VI-3 and FIG. VI-4 below.

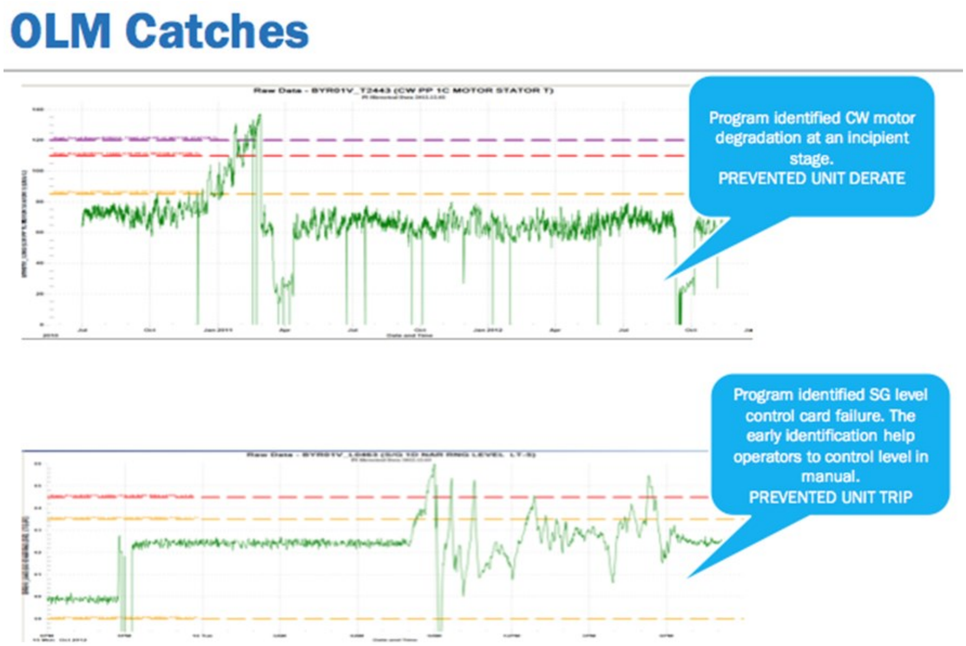


*FIG. VI-3. On–line monitoring catches (part 1).*

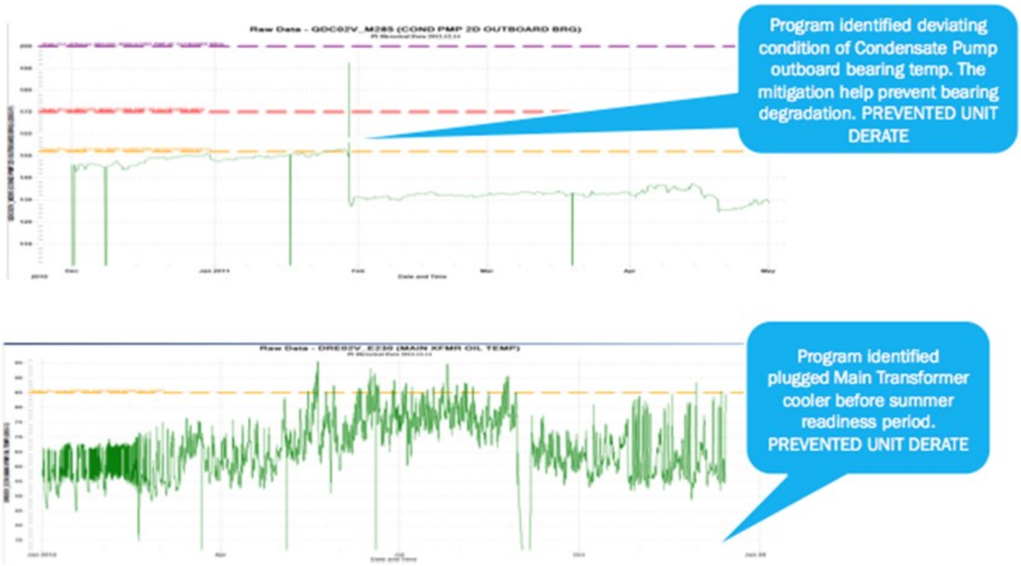


*FIG. VI-4. On–line monitoring catches (part 2).*

## VI-3. BYRON STATION WIRELESS INFRASTRUCTURE

The design of Byron wireless infrastructure was for maximum coverage both indoor and outdoor with modular installation so that areas could be added as the needs grow. FIG. VI-5 below shows Byron's design site coverage.

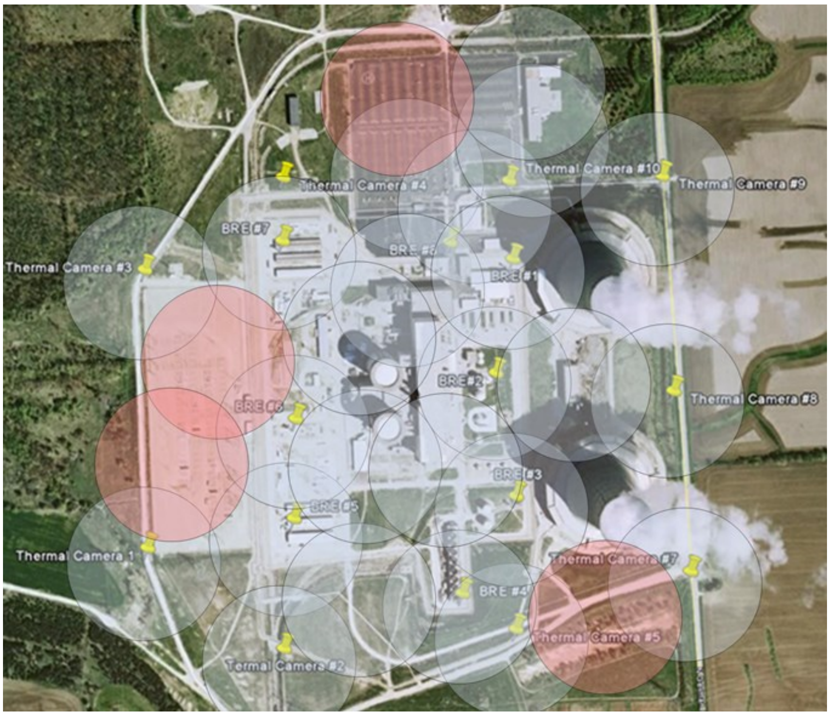


*FIG. VI-5. Byron wireless coverage.*

Services supported by the network include:

- Enterprise data (laptops, PDAs, 802.11 enabled smartphones);
- Mission critical data including sensor data and alert information;

- Wireless VOIP;
- Video transmission – IP video for compliance and security surveillance;
- RFID for asset tracking of assets, material and staff.

## VI-4. WIRELESS EQUIPMENT MONITORING

Byron's plant staff spends significant resources and time in data collection to assess real time equipment health. The time spent in data collection keeps the experts away from data analysis and prognostics. Adding wired sensors in plants are not cost effective.

Shortly after the wireless infrastructure installation, Byron Station started a number of wireless sensor projects for the following components:

- On–line circulating water pump vibration monitoring;
- Natural draft cooling towers basin level monitoring.

The IT infrastructure for wireless vibration monitoring is displayed in FIG. VI-6.

The two wireless sensor pilots were successful and Byron has undertaken additional projects to install vibration sensors on condensate/condensate booster pump (CD/CB)/motors and service air compressors monitoring. The ultimate goal of this project is to use the data to move PMs from time based to condition based maintenance. The benefit of this project will be that plant experts will spend time in data analysis rather than data collection and PMs will be performed on equipment based on real time plant data.

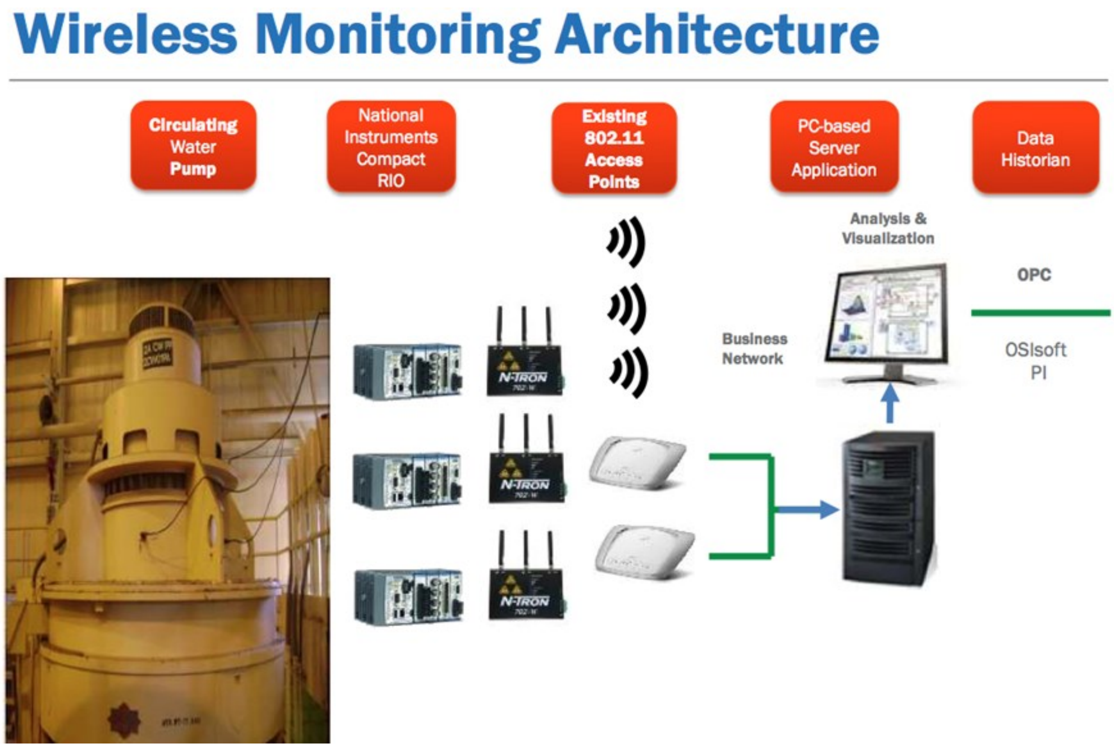


*FIG. VI-6. Wireless monitoring architecture.*

## VI-5. PROGNOSTIC HEALTH MANAGEMENT

Exelon is currently working collaboratively with EPRI and Idaho National Laboratory to develop an integrated suite of web–based diagnostic, prognostic tools and databases that include:

- Automated format of Exelon troubleshooting process;
- Capture human knowledge and retain it in digital format (KT & R).

The first deployment of the software is on the diesel generators. The elements of Prognostic Health Management are (see FIG. VI-7).

| | |
|---|---|
| Diagnostic Advisor | Identifies impending failures by comparing asset fault signatures with operating data |
| Asset Fault Signature Database | Organizes asset fault signatures collected from Exelon and across the industry |
| Remaining Life Advisor | Estimates how long an aging or faulty asset will continue to provide reliable service |
| Remaining Useful Life Database | Organizes asset remaining life signatures collected from Exelon and across the industry |

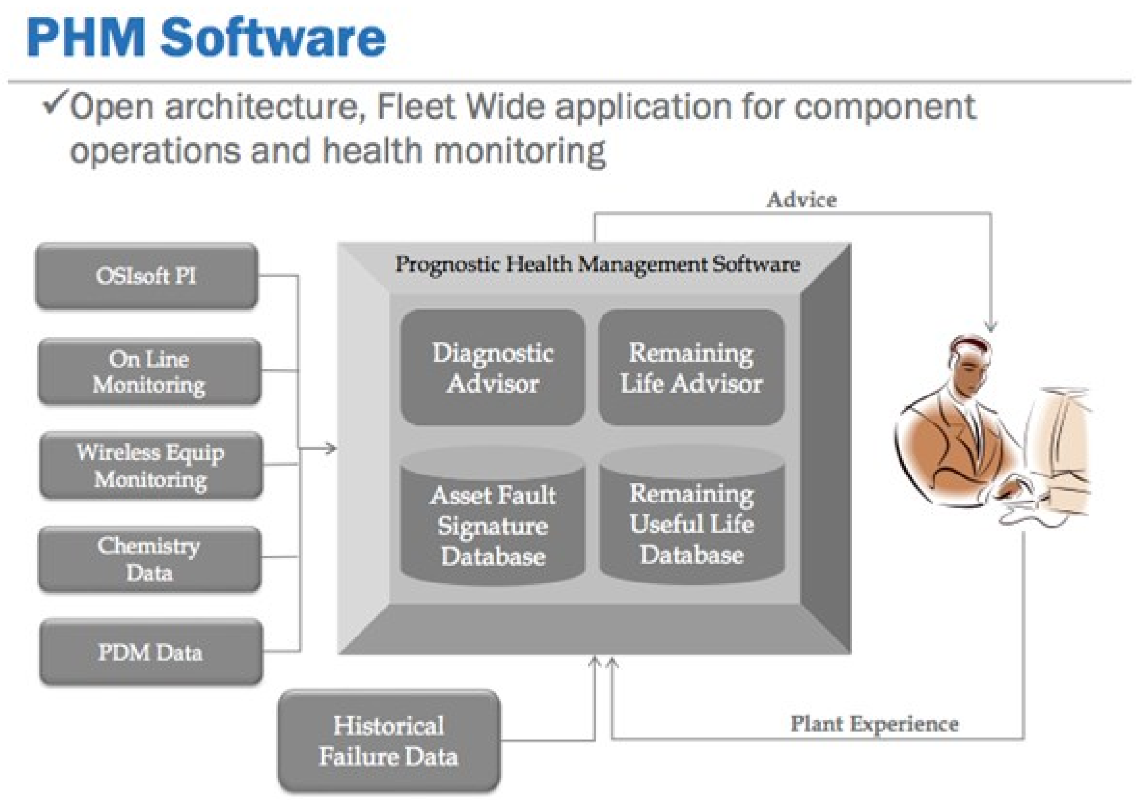


*FIG. VI-7. Elements of Prognostic Health Management.*

VI-6. RESULTS

Byron Station results from piloting CBM have been impressive:

- Engineering:
  - 10% system engineering's workload reduction by transferring engineering monitoring and trending function to on–line monitoring;
  - 30% of unexplained equipment failure can be better understood due to improved wireless equipment monitoring capabilities;
- Operations:
  - 10% Ops rounds optimized by aligning local panel data to data historians;
  - Dose reduction by remotely monitoring local data and reducing entry into high dose areas;
- Maintenance:
  - 50% of vibration specialist efficiency improvement due to on–line vibration data through wireless equipment monitoring;
  - Better vibration analysis since the expert will spend more time in diagnostics and less in data collection;
  - 20% PM reduction by switching time based PM to condition based PM.